PRINCIPLES OF SOIL TECHNOLOGY

THE MACMILLAN COMPANY
NEW YORK BOSTON CHICAGO DALLAS
ATLANTA SAN FRANCISCO

MACMILLAN & CO., LIMITED
LONDON · BOMBAY · CALCUTTA
MELBOURNE

THE MACMILLAN COMPANY
OF CANADA, LIMITED
TORONTO

PRINCIPLES
OF
SOIL TECHNOLOGY

BY

PAUL EMERSON, PH.D.
ASSOCIATE PROFESSOR OF SOILS, IOWA STATE COLLEGE

New York
THE MACMILLAN COMPANY
1936

THE SOIL

"The soil locks within its embrace the beginnings of all life and receives, at last, their discarded forms. It will outlive all the works of man, transcend all human thought. It traces the progress of history and shelters its ignoble end. It speaks eloquently and is dumb. It is the imperishable storehouse of eternity."

PREFACE

The knowledge of soils gained in the past is empirical and this knowledge has a tendency in the present to dominate the real facts. It is a common failing to assume that materials having a common name have common characteristics. Thus we are prone to view soils as essentially alike. We know, for instance, that many soils are in need of lime, but this only applies to approximately one-half of the United States. We have records of many experiments showing benefits secured by the addition of certain materials or by certain manipulations. On the other hand, data may be presented to show negative or sometimes absolutely opposite results. Evidently there are differences, fundamental differences, between the soils concerned.

The writer's long teaching experience with advanced students of soils and with graduates has convinced him that in order to understand the complex factors governing soil management and soil productivity it is first necessary that the student understand the *principle* of the soil as applied to the soil *in situ*. Such principles are just as essential to the equipment of the student of soils as the principles of bodily functions are essential to the medical student. One should know the related factors involved in a manipulation, or the possible results of a correction, before the process is applied.

While it is possible to make definite statements about a soil that will apply for a specific time and a specific location, it is practically impossible to make a general statement that will hold for all conditions. The writer has aimed to correlate the facts of soil knowledge and present the science from the teaching standpoint in as fundamental a manner as possible. It is but natural that errors, or apparently conflicting statements, will be made. The reader is asked to remember that the book is written in the interest of science of soils, and any suggestions or criticisms both favorable or otherwise that may improve the work will be welcomed.

No attempt has been made to give a complete historical or bibliographical review. The references given are selected as key material. Usually these references give a historical review of the literature and a more or less extended bibliography. In addition to the references given, a wealth of material will be found in the Proceedings of the First International Congress of Soil Science, Washington, D. C.

Acknowledgment is hereby given for the valuable assistance rendered by Dr. C. F. Shaw, University of California, Dr. F. W. Parker, Alabama Polytechnic Institute, Dr. C. F. Marbut and Dr. A. G. McCall, United States Bureau of Chemistry and Soils, Professor T. S. Buie, Clemson Agricultural College, Mr. A. M. O'Neal, Secretary American Association of Soil Survey Workers, Iowa State College, and to the large number of graduate students at Iowa State College who have assisted in various phases in the preparation of the manuscript.

P. E.

AMES, IOWA
December, 1929

TABLE OF CONTENTS

PART I

SOILS IN GENERAL: THEIR FORMATION AND CLASSIFICATION

PART IV

SOIL BIOLOGY

APPENDIX

PART I

SOILS IN GENERAL: THEIR FORMATION AND CLASSIFICATION

The soil is a distinct natural body formed by the action of many agencies through countless centuries. This body is characterized by a series of both external and internal features which are readily accessible for examination and study. Such features of the soil are "symbols" or "reflections" of its internal properties, its physical, chemical, and biological composition. These features are symbols of the condition of its genesis. For instance, the soil has (1) a definite morphology that manifests itself in its color, structure, consistence, and general profile. It has (2) a more or less indefinite petrographical composition and that imparts the textual and physical properties, giving rise to the solid, liquid, and gaseous phases and the physico-chemical structure of the soil complex. It has (3) a certain chemical composition that is usually due to physico-chemical and to bio-chemical processes subject to variation, the so-called "dynamics" of the soil mass. It has (4) its own ecology or ecological formation; for instance, its characteristic relationship to some one factor of formation, such as wind, water, etc. It has (5) a certain distribution in space, its geography, and a certain history of development, its evolution and metamorphosis. And (6) the soil has a certain genesis, having originated from certain materials (parent rock) and been formed as a result of such factors as heat, water, vegetative covering, etc. Each characteristic is manifested in a detailed study of the soil mass.

CHAPTER 1

THE PROPERTIES AND FUNCTIONS OF SOIL

One of the greatest failings of human nature is to regard lightly the common phenomena of life and things that surround us. This is especially true of the material that some call dirt, others soil, while others may casually or rhetorically use the term "Mother Earth." Whatever the term, it is always understood that reference is being made to a material in many ways subject to the will of the owner or the manipulator and usually indicating its condition by the crops produced. This is the material forming the basis of civilization, yet we actually know little of the complicated processes it has passed through in its formation or of the processes continually taking place within it. Viewed from a standpoint of plant and animal growth we may rightly assume that this material is the only material capable of functioning for the benefit and support of man. Surely such a material is worthy of close attention and study.

1. The Soil Yardstick.—To the geologist the soil spells an evidence of certain ancient activities; to the physicist, chemist, and biologist it is a material replete with vast unsolved problems involving the greatest skill to solve, but to the agriculturist it is a medium in which he may grow his crops.

The measure of a soil does not lie in the inherent characteristics of the material itself; rather it lies in the latent possibilities of the mass. The measure of a soil (the combined factors determining its value) lies in its ability to produce crops. Due to the fact that the soil itself is only one of a number of factors influencing crop production, it is easily seen that the soil yardstick (crop-producing power) is a variable factor.

2. Soil Defined.[1]—The greater portion of the material commonly spoken of as the soil was originally in the form of rock matter, which by various processes was broken into very small particles. A much smaller portion of this soil was in the form

[1] For complete definitions see "Glossary of Terms."

of growing plants which have died, decomposed, and become more or less intimately mixed with the rock portion. This material forms a basis for the usual definition: soil is "finely divided rock material mixed with decayed vegetable or animal matter, constituting that portion of the earth in which plants grow."

The soil is such a wonderful aggregation of complex realities, full of apparent self-contradictions, that it loses its interest as a dynamic entity directly it is defined in sharp lines. The problem of definitely defining the soil is as difficult, or as impossible, as that of defining a great nation of people. It is obvious therefore that, while a definition is desirable and necessary, a perfectly satisfactory scientific definition is difficult. As applied to the soil, it may be said that any general conclusion, fact, rule, or law, must be subject to exceptions. This is due to the fact that nature is continuous, consequently there are no distinct and continuous lines.

The agriculturist, however, requires that the material in his fields be more than a mere medium for supporting the growth of any kind of plants. He demands that his soils be able to support the growth of such plants as will give him an economic return. The following pages will show that the influence of the soil on the growth of plants is dependent upon physical, chemical, and biological forces, that these forces may work together or work opposite to each other, and that plant growth is affected according to the sum total of the forces in operation.

An assembling plant may have all the necessary parts for the formation of an engine, but until these parts are properly fitted together and properly functioning, the engine will not be able to work. So with the agricultural soil, all forces must be properly adjusted and functioning for best crop returns. We must define our soil in recognition of these forces. Agricultural soils, therefore, may be defined as "a heterogeneous collection of rock and mineral fragments of varying thickness and arrangements whose decomposition and disintegration has been brought about by the action of physical, chemical, and biological forces, working singly or in combination, and containing sufficient decomposable plant remains to serve as a source of energy in stimulating the action of these forces to produce soluble plant food in an amount sufficient to support the growth of plants commonly used in agricultural pursuits."

3. The Soil an Intangible Material.—An agricultural soil is a material possessing certain properties defying description; for instance, that intangible factor often spoken of as "life." If we take the various soil-forming rocks, crush them to the fineness of soil particles, add organic matter, the proper amount of water, inoculate it with soil micro-organisms and try to grow plants in the mixture, the results will be disappointing. If the mixture is allowed to stand for a long time the results will be better. On the other hand, if a productive soil is sterilized, either partially or completely, if it is treated with various solvents, or is allowed to dry for a long time, it will produce a poor plant growth. In other words, the soil is not entirely an inert material but possesses some factor or factors capable of being destroyed or limited, much the same as the factor of life may be destroyed or limited. The life factor of soil is injected by the forces of nature and cannot be produced artificially. When destroyed it can only be restored by natural processes.

4. Soil Is Not Dirt.—Some farmers speak of the material in their fields as "rich dirt" or "poor dirt," others may speak of the same material using the term "soil." In either case the same idea is expressed, namely, the material is regarded as a basic medium for the production of crops. If the soil produces large crops it is rich, if small crops it is poor. While the term "dirt" (matter out of place) has no relation or connection with the term "soil," it is commonly and incorrectly used by many.

5. The Visible Properties of the Soil.—Apparently nature abhors a bare spot. She makes every effort to have plants growing in all conceivable positions wherever there is sufficient moisture and a suitable temperature. If the soil is disturbed or the vegetation upon it destroyed, it will soon be covered with a new growth. Certain soils may be better adapted to the production of certain crops than are others, due to their location, mechanical composition, or peculiar characteristics; consequently we have field soils, garden soils, truck soils, orchard soils, etc. It appears then that no matter what the condition of a soil may be, its natural and visible function is the support of plant life, both from the mechanical and nutritional standpoint.

6. The Invisible Properties of the Soil.—The soil is never in a state of equilibrium, that is, it is never in a state of complete rest. The visible properties of the soil are dependent upon the

favorable continuity of the invisible forces which are always present in a more or less active form. They may be grouped under the heading of the physical, chemical, and biological functions. As will be shown later, these forces are so closely correlated that it is difficult to determine the effect of any one upon plant growth without considering the others. Further, they do not always operate favorably for plant growth and may be in direct opposition to each other. While the effect may sometimes be seen, the direct cause of the effect may be very difficult to determine.

I. The Physical Function of the Soil.—The physical properties of the soil are chiefly concerned with the size and arrangement of the different particles and their relation to the moisture, temperature, and air supply of the soil as a whole. The best growth of plants is obtained in a soil having a certain moisture and air relationship and a definite range of temperature. These conditions are in turn dependent upon such factors as the mechanical composition, the organic-matter content, the color of the soil, the influence of external conditions, and the functioning of the chemical and biological forces. The proper physical condition of the soil is a most important consideration in the growth of economic plants.

II. The Chemical Function of the Soil.—The soil may be looked upon as a great incomplete chemical structure. It is composed of the various compounds in the soil mass, all of which are more or less soluble. As all agricultural soils contain more or less water and as chemical compounds in solution have a tendency to react with each other, it is readily apparent why the soil is never in a state of equilibrium. Compounds are constantly being precipitated while others are constantly going into solution. As the moisture content is continually changing, the action is constantly being retarded or accelerated. The physical condition of the soil has a marked influence on the process, while the biological action is constantly adding new stimuli. So many compounds are involved and so many varying conditions are constantly being introduced that little is known of the actual process. The physical condition of the soil may be markedly changed by the action of the chemical forces and vice versa.

The chemical functions appear to be very broad in scope. The reactions involved in the production of materials for plant use are apparently only a small portion of the actions and reactions

continually taking place. The soil would be nothing more than a mechanical support for plants, should its chemical functions cease.

III. The Biological Functions of the Soil.—The soil is populated by a large flora and fauna. This life consists of many plants and animals that make their home, either partially or completely, in the soil. These plants and animals belong mainly to the lower forms of life and are usually dependent upon the soluble carbohydrate material for their food supply. A few of the forms may be seen with the naked eye, but the majority are so small as to require the microscope. They feed upon and decompose the remains of the higher plants or they feed upon each other. In doing this they serve as the connecting link between the kingdom of the living and the kingdom of the dead. They are in reality the stomach of Mother Earth, as they digest the complex remains of the higher plants and thus release the elements locked up in the tissues for the use of other plants. In the process of digestion they produce certain actions and reactions that stimulate the chemical functions and influence the physical functions. Certain of the biological forms are very beneficial to plant growth, others are very detrimental, while many of them have no direct relationship. Biological activities are influenced directly by the functioning of the chemical and physical forces. The activities of the biological forces are usually interpreted by chemical means.

7. The Soil as the Source of Life.—All life originates from and returns to the soil. All animals are dependent upon plants for their sustenance, while plants are in turn dependent upon the soil. Not only are plants dependent upon the soil for their mechanical and physical support, but the roots are continually drawing upon the soluble materials of the soil for certain combinations of elements that serve the plant as food. The total amount of the soil-derived elements forms only a small portion of the entire plant, yet they are so absolutely necessary for development that no growth will take place without them. When the plant or animal dies and its remains come in contact with the soil, it is decomposed and the elements freed in their simplest combinations. These elements were originally derived from the soil and are now returning to serve as food for the next generation. The action is suggestive of a cycle requiring various lengths of time

for completion. The plants are continually drawing life-giving materials from the soil, animals are continually feeding upon the plants and continually returning to the soil the residues, and in the end are returned to the soil themselves. Briefly stated, "We borrow from the soil that which is essential for our life to-day, but when that brief day is ended return it once more, with neither loss nor gain, to its original source."

8. A Modern Concept of the Soil.—Whitney [2] believes the soil acts as a living thing. Its function may be likened to an animal from the standpoint of color, skeleton, tendons and muscles, colloidal lining, digestive system, respiratory system, and circulatory system. The color of the surface is taken as an indication of the adaptability of the soil to a general class of crops. The color of the surface area is only an indication that must be confirmed or rejected by an examination of the color of the same soil at different depths. The skeleton is the framework or structure of the soil. The function of the skeleton depends upon the different-sized particles and their arrangement. The tendons and muscles are those materials affecting the physical functions. The colloidal content is assumed to act in this capacity. The colloidal lining is a result of the action of the colloidal content in absorbing and regulating the supply of nutrient materials. This action may be considered as a chemical function. The digestive system is a result primarily of biological activities in decomposing or changing the various materials, especially organic matter, added to the soil. The respiratory system is the air in the soil. The respiratory processes are closely connected with the circulatory, or the movement of the soil water. In other words, the soil is regarded as a dynamic force acting as a medium for, and a regulator of, plant growth.

[2] Whitney, Milton. *The Soil and Civilization.* D. Van Nostrand Company. New York, 1925. 278 pp.

CHAPTER 2

SOIL FORMATION

The mineral portion of soil consists of the more or less stable débris left by the action of various agencies in breaking down the earth's crust. In other words, soil is the result of rock decay, is born of rock, and in the decay process the original constituents have been more or less changed. In some cases, the original rock form is apparently unaltered. In the majority of cases, however, no indication is given of the form of the original material.[1]

9. The Derivation of Soil.—Since all soil has been derived from the earth's crust, regardless of the process involved in its formation, we may expect that the composition and character of the crust would have a marked bearing on the composition and characteristics of the soil formed. However, it must be remembered that the soil constituents are as old as the earth itself, and that the soil is the result of the activities of various agencies. As the action of these agencies has tended to mix, move, and modify the results of rock decay, it follows that our soils have been derived, not only from the crust underlying them, but from areas more or less distant.

10. Origin of the Earth.—We know practically nothing of the origin of the earth. Many hypotheses have been advanced but objections may be made to any or all of them. The most logical have been developed, not by observation of the earth itself, but by astronomical studies of the different solar systems. The theories regarding the origin of the earth may be grouped under the following hypotheses:

I. Nebular.—Gases collect into a spheroid by gravity and loss of heat. These attract to the mass more gases.

II. Meteoric.—A swarm of meteorites collect or form an aggregate.

[1] For a well illustrated, non-technical discussion of the nature, characteristics, origin, and formation of soil, see Shaler, N. S., "The Origin and Nature of Soils," *12th Annual Report, U. S. Geol. Survey, Part 1*, pp. 219-345. 1891.

III. Planetesimal.—Small bodies moving in an orbit about a common center, forming a disk-like system, gradually come together.

Each of these hypotheses presupposes a building up or additional process during which the earth gradually grew and took form. For instance, it was at first without form (Nebular Stage), but collected about a nucleus (Nuclear Stage) which gradually increased in size. The increase in size increased the attractive properties of the mass which in turn held permanently the lighter free molecules such as form our present atmosphere (Initial Atmospheric Stage). The attraction of particles of varying composition, particularly radio-active matter, caused compression on the interior, the generation of heat, the liquefaction of the most fusible portions, the rise of lava, and the formation of volcanoes (Volcanic Stage). Further growth resulted in the attraction and holding of water in the form of vapor (Hydrospheric Stage). The condensation of the water vapor provided a suitable condition for the introduction of life as it is known to-day (Initial Life Stage) and the surface of the earth was no longer subject to universal burial.[2]

11. The Earth's Crust.—The crust of the earth may be likened to a covering of slag or scoria over the interior. Nothing is known of its thickness, which is evidently quite variable; but for the purpose of computation, based upon geological observations, an average thickness of twenty miles may be assumed. Clark[3] estimates the crust to consist of the following rock constituents:

Igneous rocks,	95 per cent	Shales,	4 per cent
Sandstones,	0.75 per cent	Limestones,	0.25 per cent

This estimation is made upon such a broad scale that deposits like coal made only a slight difference in the figures and no attempt was made to include them. The material of the above rocks has been derived from the following sources: 92 per cent from the solid portion of the earth; 7 per cent from the waters of the earth, and 0.03 per cent from the atmosphere.

[2] See Fairchild, H. L., "Our World in the Making," *Science*, n.s. *64*, pp. 365-371. 1926. John, John, *The Surface History of the Earth*. Oxford University Press. 1925. 192 pp. For a non-technical discussion see Lee, W. T., *Stories in Stone*. D. Van Nostrand Company. New York, 1927. 266 pp.

[3] Clarke, F. W., "The Data of Geochemistry," *U. S. Geol. Survey Bul 695*. 1920.

The earth's crust may be divided into three more or less well-defined layers. First and innermost, there is the shell of igneous or plutonic rocks which is of unknown thickness and which forms the nearest approach to the original material of which the crust was composed. At the present time very little of the exposed portion of the earth's crust is of plutonic origin. This innermost shell is overlaid with a second shell, comparatively thin, consisting of sedimentary and fragmental rocks, the upper portion of which is being decomposed and disintegrated to form the third layer of unconsolidated material, the boulders, gravels, sands, clays, etc., which in turn give rise to the mineral portion of soils.

12. The Formation of Rocks.—The first rock formation on the earth was due to the cooling of the surface of the magna. The rocks thus formed are called *igneous,* formed through the agency of heat. Such rocks may be of an indeterminate substance like glass or they may be a mixture of definite mineral species. These rocks existed before any form of known life was possible on the earth and before the process of active decomposition and disintegration began. When the surface of the earth cooled sufficiently to allow water to fall upon it, the igneous rocks began to decompose and disintegrate, and in their place other rocks were formed. The majority of these rocks owe their origin to the action of water, hence are spoken of as *aqueous.* The constituents of aqueous rocks may have been at one time in solution and deposited by precipitation, evaporation, cooling, action of water-loving animals, etc., or the residue from the solution may be reconsolidated by pressure, the injection of cementing materials, etc. When either an igneous or an aqueous rock has been transformed from its original form into another more or less distinct form, it is placed in a third group. Such rocks are spoken of as metamorphic. The aqueous rocks are the most important source of soil-forming material.

The statement has been made that "soil is born of rock." We may also add that some rocks are simply consolidated soils. A quartz rock decomposes, forming sand; the sand may consolidate into sandstone. Feldspars decompose to form clays, which in turn may consolidate into slate. Sand ripples, foot-prints, etc., made in prehistoric times and preserved in solid rock are mute evidence that our soils may have passed through a number of rock-soil transformations.

13. Agricultural Geology.—A study of the earth and the various factors concerned in its formation and subsequent changes rightfully belongs to the science of geology. The agriculturist, however, is only concerned with that thin mantle of rock débris in which his crops are grown. As a consequence, he is interested in those geological stages giving rise to the soil as it exists at present.

While this mantle has been formed mainly of rocks, it exhibits only in a slight degree the characteristics of the parent rock. It has evolved through a long process of changes, was formed as a result of evolutionary changes, even now is changing and will continue to change to the end of time. Soils, therefore, can only be regarded as dynamic in character. As soil always has existed and always will exist, it becomes of interest to discuss briefly those geological ages contributing to the dynamic character of the soil mass as it exists at present.

14. Geological Ages of the Earth.—It appears that practically the entire surface of the earth was at one time under water, being the bottom of either an ocean, great inland sea, or lake. Gradually the land emerged from the waters, in some cases to be submerged again and again; in others, to be more or less permanently exposed; but in all cases to bear mute evidence of the various factors concerned in its formation. These factors have been used by geologists as a basis for grouping the age of the earth into eras. The names given the main groups are as follows: Archeozoic, Proterozoic, Paleozoic, Mesozoic, and Cenozoic. The influences of the different eras on soil characteristics are briefly discussed.

I. Archeozoic.—The Archeozoic geologic era is the oldest formation known. It consists primarily of an intricate structure of igneous rock formations that at present are buried under the deposits of later ages, which are merely the reworked material derived from the rocks of this age. As some carbonaceous material and some limestones may be found in the few exposures of this age, the inference is drawn that some form of life existed at the time. The age, however, is generally considered as lifeless.

The formations at this time were merely the basis from which the materials for all subsequent formations were derived. The agencies of formation were physical and chemical, the latter possibly being the more important. At the end of the period,

the topography of the earth's surface was doubtless uneven and mantled with rock débris which had arisen from the decay and weathering of the rock surface.

II. Proterozoic.—The first sign of extensive rock weathering, with its resultant soil formation, appears in the Proterozoic era. The slow transgression of the seas and streams worked over the decayed rock mantle of the previous age, separated the mud, sand, and gravel, transported the particles various distances and deposited them. The ceaseless pounding of the seas caused the moving water to exert its full force in further decomposing the exposed rocks. The sedimental material became cemented or solidified, thus forming shales, sandstones, conglomerates, etc. The deposits of carboniferous shales, slates, chists, and limestones indicate plant life.

III. Paleozoic.—During the early part of the Paleozoic era, the seas covered the land with a progressive submergence. Large quantities of sedimental material were moved with a consequent lowering of the land and rising of the seas. During the latter part of the period, there were extensive withdrawals of the sea over the North American continent, followed by re-invasions. During the intervening periods, extensive salt and gypsum beds were formed. Toward the end of the era, the Appalachian Mountain system began to develop, also the area to the west, extending to the present Great Plains area, gradually rose from the bottom of the sea and became land.

The large number and variety of fossils found in the deposits of this time characterize the era as ushering in the lower forms of marine life which were closely followed by the lower forms of animal life on land. Every great division of the animal kingdom except the vertebrate is represented. The shells of some of these animals, particularly the crinoids, had much to do with the formation of limestones or in influencing the character of the sediment deposited by the waters. Plant life also appeared at this time, growing in the shallow ponds. Due to favorable climatic conditions at the later part of the era, plant life became very luxuriant, making possible the vegetative growth necessary for the formation of our present coal beds.

IV. Mesozoic.—From the standpoint of life, the Mesozoic geologic era is known as the age introducing mammals on the earth. From the standpoint of soils, the era is characterized

by the gradual rise of the entire continent of North America with the exclusion of the sea, the development of the Atlantic coast east of the Appalachians, the gradual rise of the western interior, and the gradual retreat of the Pacific Ocean on the west coast. The earliest period (Triassic) in the era was evidently one of widespread aridity and great changes of temperature, which had a marked influence on vegetation and in disintegrating the exposed rock surface. The second period (Jurassic) was characterized by a genial climate that favored both land and marine life. During this period an arm of the Pacific covered much of the states of Wyoming, Montana, and Utah, overflowing into South Dakota, Colorado, Arizona, Nevada, and Idaho. It undoubtedly entered the United States by way of British Columbia and Saskatchewan. The third and last period (Cretaceous) is marked by the appearance of volcanic activity and the gradual encroachment of the sea on all sides. At first there was a submergence in Mexico, Texas, and on the Pacific coast followed by a long period of erosion in the exposed areas. Finally, the sea overflowed the coastal plain of the Atlantic and the Gulf of Mexico. The encroachment from the Gulf of Mexico submerged the great plains of the middle portion of the United States. This submergence extended possibly as far as the Arctic Ocean. At the end of the period the sea withdrew, leaving the land area much as it is at present.

The appearance of volcanoes at this time had possibly a marked influence on soil formation; certainly they introduced another agency in decomposing rock masses. These volcanoes were apparently formed as vents for the release of gases under the earth's crust. Some of the liquid (molten rock) flowed out as lava and formed rocks, some was forcibly expelled to great heights and striking the cooler air above broke into small fragments and fell back to the earth's surface as ash. This ash was seized by the wind, blown in all directions, and possibly carried to all corners of the earth.

In addition, the materials from the volcanoes were mixed with great quantities of gases and superheated steam.[4] The hydrogen burned to form water, the sulphur to sulphur dioxide. The steam reacted with the metallic chlorides and the sulphur dioxide to

[4] The steam in some cases is so hot that it will char a wooden stick. *National Geographic*, *33*, p. 123. 1918.

form hydrochloric and sulphuric acids. As these acids were forced through the mass of rock material, they produced a great many chemical changes.

V. Cenozoic.—The Cenozoic era is known as the age of mammals and the era of modern life. It is divided into two periods, the Tertiary and the Quaternary. The Tertiary is characterized by changes in the topography of the dry land. During this period, there was an extensive folding of the surface with the formation of mountains and a stimulated volcanic activity. The steep slopes of the mountains afforded favorable conditions for erosion by both wind and water. As the river systems were not so well established as at present, the sediment carried by the water was deposited in the lower areas as alluvial fans, etc.

The second period, Quaternary, of this era is of extreme importance from the standpoint of soil formation. Nearly one-half of North America became periodically covered with thick sheets of ice, having the slow movements of glaciers. The ice tended to accumulate in three centers and radiate in all directions. The main centers of accumulation were in Canada, the eastern (Laboradorean) was in the north central part of the province of Quebec, the central (Keewatin), which was also the largest, was immediately west of the Hudson Bay in the northern part of Manitoba, while the western and smallest (Cordilleran) was in the Canadian Rockies. The Cordilleran occupied a plateau hemmed in by mountains covering practically the entire province of British Columbia and extending southward in the United States to a point midway of the state of Washington and the panhandle of Idaho. Local glaciers occurred at the same time as far south as New Mexico, Arizona, and California.

15. Glacial Stages.—The periodic invasion of ice from the other two centers of accumulation, the Keewatin and the Labradorean, covered the balance of the northern part of the United States. The southern boundary of the invasions may be roughly marked by a line drawn west to east from the Cordilleran glaciation in Idaho through the center of Montana, then following the Missouri and Ohio rivers to the Pennsylvania line, continuing eastward through Pennsylvania and the north central portion of New Jersey into the Atlantic. The invasion consisted of a long period during which the area was covered with ice. This period was followed by a long interglacial period during which the

climate sometimes became mild enough to support a luxuriant vegetation. The stages of the glacial periods are as follows:

I. Jerseyan Glacial Stage.—Appears in New Jersey and on the Allegheny and Upper Ohio rivers. The greater portion of the drift is buried beneath later invasions. Ice probably originated in all three centers of accumulation, as evidences of this invasion have been found in Montana and Colorado.

II. Aftonian Interglacial Stage.—Represented by an irregular sheet of sand and gravel in Iowa.

III. Kansan Glacial Stage.—Appears on the surface in Kansas, Missouri, Iowa, and Nebraska as an extended sheet of clayey material (Kansan till). Ice presumably originated in the Keewatin and Labradorean centers.

IV. Yarmouth Interglacial Stage.—Represented by an old soil occurring in eastern Iowa where the Illinoian till overlaps the Kansan till.

V. Illinoian and Iowan Glacial Stage.—The Illinoian drift was presumably formed by ice originating from the Labradorean center. It appears on the surface in the southern and western part of Illinois, with smaller exposures in the states adjacent to the east and north. The Illinoian till is clayey with little assorted material. The Iowan drift was formed from the Keewatin center and lies in a thin sheet over the Kansan till in the northern and eastern part of Iowa, extending into Minnesota. The Iowan drift is characterized by many boulders. There is some question as to whether the two invasions were simultaneous.

VI. Sangamon Interglacial Stage.—Represented by sandy deposits overlying Illinoian drift in Illinois.

VII. Wisconsin Glacial Stage.—This is the last stage of the glacial invasions, consequently the original developments are more or less well marked on the surface. The invasion originated in the Labradorean center, advanced over New England, New York state, and into Pennsylvania, Ohio, Indiana, Illinois, and Iowa. The Labradorean invasion was joined by invasions from the other two centers of accumulation until possibly the entire northern portion of the United States was covered with ice.

VIII. The Present Stage.—As the glacier retreated, it left numerous lakes, formed numerous rivers and certain topographical characteristics. The present may be considered as merely an interglacial stage.

16. Glacial Action.—The exact cause of glacial formation and subsequent inundation of great areas with a heavy mantle of ice and snow is not known. Humphreys [5] shows that they have occurred periodically and it is quite probable that we are now living in an interglacial period.

The glaciers originated in Canada and extended southward as great walls of snow and ice of almost incredible thickness and weight. The great pressure (40 pounds per square inch for each 100 feet of thickness) levelled hills, filled valleys, gouged out great rocks, ground them to pieces or transported them far from their original location. The rock flour and débris was deposited as a mantle over the surface of a great area. Not only was the area covered by ice affected, but the water flowing from the melting glaciers extended its action to great distances. It is estimated [6] that approximately 4,000,000 square miles in North America were covered by glaciers and about 20 per cent of the United States is influenced by the débris.

The action of glaciers on soil formation is of decided interest because it is more pronounced and more in evidence than that of the usual world-wide soil-forming agencies. Undoubtedly much of the soil material in the sections affected by glacial action is merely reworked weathered material, formed through natural weathering agencies during the previous geologic areas. Glacial soils are an expression of the violence of nature; other soils, derived through millions of years of weathering, are an expression of nature in a placid state.

17. Soil-Forming Agencies.—The agencies of soil formation may be grouped under the headings of weathering, denudation, and deposition. As defined by Foye,[7] *weathering* "is the alteration of rocks rending them liable to transportation by the dynamic forces having their origin near the surface of the earth" (disintegration and decomposition); *denudation* "as the removal of the products of rock weathering by the dynamic forces having their origin near the earth's surface." The forces engaged in the transportation of soil-forming material cannot move rock materials

[5] Humphreys, W. J., "Factors of Climatic Control," *Journal Franklin Institute,* Vol. 189, No. 1, pp. 63-98. 1920.

[6] Lyon and Buckman, *The Nature and Properties of Soils.* The Macmillan Company. New York, 1926. 588 pp.

[7] Foye, W. G., "Denudation," "Erosion," "Corrosion," and "Corrasion," *Science,* n. s., *54,* pp. 130-131. 1921.

until it is first broken down by the chemical and mechanical activity of weathering. When the material is broken down, it may be eroded, transported by various agencies, and deposited. Denudation then is the combined process of erosion and transportation. *Erosion,* however, is a result of physical and chemical forces taking place as follows: (1) physical, the mechanical wearing away of rocks (abrasion) by wind, running water, moving ice, and gravity; (2) chemical loss (corrosion) due to chemical actions and reactions.

18. Classification of Soil-Forming Agencies.—The agencies concerned in soil formation may be classified as follows:

I. Weathering.	Water	Mechanical: Frost. Chemical: Hydration, Oxidation, Solution.
	Temperature	Mechanical: Expansion, Contraction. Chemical: Stimulation or Retardation.
	Gases	Chemical Action: Oxidation, Carbonization.
	Plants and Animals	Mechanical: Root growth, Burrowing, etc. Chemical: Acids from roots, Action of excreta and decaying organic matter.
II. Denudation and Deposition, involving Erosion, Transportation, and Deposition.		Wind. Running water. Ice, usually in motion. Gravity.

These various agencies will be discussed in detail in later chapters.

19. The Processes of Soil Formation.—The various processes of soil formation taking place through the millions of geologic years, and still continuing to-day, may be grouped according to the resulting material under two headings:

I. Disintegration.—The processes resulting in a breaking down of the mass of rock or rock material into smaller and still smaller particles. There is a marked change in the physical characteristics of the resulting material but little or no change in the chemical content of the particles themselves. The action is analogous to the grinding of a rock.

II. Decomposition.—The processes resulting in a breaking down of the mass of rock or rock material with a change in its chemical composition.

The net result of both of these processes throughout the ages has been a progressive series of changes during which the rock mass has been altered (metamorphosed) into the material of the soil mass. These processes have been, are now, and will be active. New soils are being formed; old soils are undergoing change. Thus, from the standpoint of soil age, we have such successive stages of formation as recent, young, youthful, immature, mature, and aged soils.

20. Classification of Soil-Forming Processes.—The processes of the disintegration and decomposition may be classified as follows:

I. Disintegration: The physical (mechanical) function of soil.
 (1) Soil Material Moved Very Slightly: Temperature changes. Frost, exfoliation, difference in coefficient of expansion, etc.
 (2) Soil Particles Moved Small Distances: Caused by plants and animals.
 (3) Soil Particles Moved Usually Great Distances: A result of erosion and deposition. Caused by water, ice, and wind.

II. Decomposition:
 (1) Direct Process: The chemical function of soil formation.
  (a) Oxidation and deoxidation.
  (b) Carbonation and decarbonation.
  (c) Hydration and dehydration.
  (d) Solution.
  (e) Physico-chemical process.
 (2) Indirect Process: Mainly biological.
  (a) Metabolic processes affecting the organism internally, assimilation, etc.
  (b) Metabolic processes affecting the external environment of the organism, enzymes, etc.

21. Forces Involved in the Earth's Formation.—As the temperatures of the prehistoric earth were evidently such as to prevent the existence of any known form of life, it is difficult to conceive that the earlier stages of the earth's formation could be ascribed to any other agencies than those of chemistry and physics. Washington [8] shows that the chemical reactions involved

[8] Washington, H. S., "The Chemistry of the Earth's Crust," *Annual Report Smithsonian Institution*, pp. 269-318. 1920.

apparently followed certain peculiarities of the periodic table which may possibly be explained on the basis of physical-chemical laws.

The soil, as it exists at present, is a result of three main forces, the physical, the chemical, and the biological. Each of these forces has contributed to the various conditions affecting its genesis. In the majority of cases, the action of these forces is interdependent. In a few cases, the action of one force may predominate. The importance of each of these forces will be brought out in the following chapters.

CHAPTER 3

SOIL GENESIS

The soil, as it exists at present, is a result of widely differing climatic, geologic, topographic, and biologic conditions that have continued through unmeasured ages. From the climatic standpoint, the development has been under all degrees of temperature, from the extreme cold of the polar regions, through the milder conditions of the temperate zones, to the heat of the tropics. Each of these zonal divisions has more or less definite areas of rainfall, ranging from the waterless areas of the desert, through the arid, semi-arid, feebly arid, semi-humid, to the humid, and possibly the super-humid areas. From the geologic standpoint, the parent rock in one area may be similar to or entirely different from that of another. From the topographic standpoint, the elevation in any climatic area may range from sea level to the highest mountain. From the biologic standpoint, the development has been under different kinds of vegetative growth.

22. Soil Genesis in the United States.—The continent of North America is quite different climatically and topographically from that of the other continents. It is characterized by increases in temperature in almost parallel lines, from the North to the South (see Chart No. 1, Average Length of Growing Season, p. 338), and by a wide range of precipitation, the lines of which are roughly at right angles to the temperature lines. (See Chart No. 2, Average Annual Precipitation, p. 339.) The topography differs from that of other continents in that the center of the area is occupied by an immense fertile plain, while the mountainous areas are at either border and extending from the North to the South. (See Chart No. 3, Land Relief of the United States, p. 340.)

The great plain area, between the mountainous sections, is possibly the oldest of the various soil areas. The southern part has developed under natural weathering conditions; the northern and more recent portion is a result of glacial action. The soils of the mountainous section have been developed more or less in

place. Between the mountains and the sea, the development is mainly due to the action of receding waters. This action has been quite extensive along the eastern coast, and practically nil along the western coast.

23. The Placing of Soil.—During the earlier geological eras, the mineral portion of our present soils was subjected to the forces of weathering that gradually decreased the size of the rock masses and gradually covered the surface of the earth with a mantle of unconsolidated material. This incoherent mass, whatever its nature or origin, varying widely in thickness and composed of materials essentially the same as those which make up the rocks themselves, but in greatly varying conditions of mechanical aggregation and chemical combination; is referred to by Merrill [1] as "the Regolith." In some places, this mantle originated from the underlying rocks, but in the majority of cases it is the result of denudation and deposition. Thus, we have a gradual formation of soil in place. First, the weathering and breaking down of the rock face with the formation of smaller rock fragments. These fragments in turn were broken into still smaller particles, which may or may not have been transported to other areas. In any event, there was a gradual shifting, assorting, and building-up process resulting in the solid rock mass becoming covered with its fragments, on top of which, in varying gradation, were admixtures of still smaller fragments, until finally the surface became covered with the particles to which we give the name soil.

24. The Genetic Grouping of Soil.—The so-called "Geologic Classification of Soils," [2] based on the climatic and geologic forces that have functioned in the placing of soil, may be used as a basis for illustrating the genetic grouping of soil. The classification and discussion of the various formations follow:

I. Soils formed in place—sedentary soils.
   (1) Residual: Soils formed by the chemical action of decomposition and the physical action of distintegration **(25)**.
   (2) Cumulose: Soils formed under swampy or marshy conditions **(26)**.

[1] Merrill, G. P., *Rocks, Rock Weathering, and Soils*, pp. 299 f. The Macmillan Company. 1897. 411 pp.

[2] Emerson, P, *Soil Characteristics*. McGraw-Hill Book Co., New York, 1925. 222 pp.

II. Soils moved—transported by various agencies from their point of origin and deposited in a new location.
  (1) Colluvial: Soils moved by the action of gravity. The débris (talus) at the base of cliffs **(27)**.
  (2) Water-formed: Soils moved by the action of water **(28)**.
    (a) Marine or sea-laid soils. Formed at the mouths of rivers, along sea coasts, salt marshes, bars, etc.
    (b) Lacustrine or lake-laid soils. Beds of extinct lakes, beaches and terraces, remains of old water levels and shores.
    (c) Alluvial or stream-laid soils. Soils deposited along streams, the first bottom or present flood plain, the second bottom or terrace lands, exposures due to change of river bed, deltas, etc.
  (3) Glacial: Soils resulting from the action of ice **(29)**. Gravels, sands, silts and clays or admixtures of characteristic topography and formation.
  (4) Loessal: Soils deposited by the action of wind **(30)**. Fine grained soils, loess, adobe, dune sands, etc.

Soils Formed in Place

25. Residual Soils.—Such soils supposedly result from the action of forces causing very slight movement, the disintegration and decomposition of rock material in place. Almost whole states are made up of soils of this formation. In the eastern portion of the United States, practically all of the Piedmont **(70)**, Appalachian Mountains **(71)** and the Limestone Valley **(72)** Provinces are residual. In the western portion of the United States west of the fringe of loess, there are other great areas of residual soils. Under favorable climatic conditions, as in the east, these soils may be very productive; under less favorable conditions, as in the areas of limited precipitation, the soils are used mainly as pastures.

26. Cumulose Soils.—Soils consisting of a combination of a large amount of organic matter, mixed with small but varying amounts of mineral matter, are spoken of as Cumulose soil. The organic matter was formed in place by the growth of all kinds of water-loving plants, mosses, sedges, grasses, etc., forming in the undrained state bogs, marshes, and swamps. The vegetation

grew, died, was partially or entirely covered with water, passed through a more or less incomplete stage of decomposition and settling to the bottom, accumulated often in deposits of great thickness. By this accumulative action, bodies of water often became filled with the deposits of organic matter. The areas, however, were always subject to mineral material being brought in by both wind and water action, consequently cumulose soils from the organic matter standpoint may be regarded as strictly residual. These soils usually do not cover extensive areas, rather they are in isolated, more or less limited, tracts. These tracts are limited to certain portions of the United States, as shown by the map illustrating Chart 4, p. 341.

TRANSPORTED SOILS

The transported soils are of the greatest agricultural importance. They are grouped as colluvial, water, and wind-formed areas.

27. Colluvial Soils.—Soils formed by the force of gravity. They are of little agricultural importance except in cases where, due to creep and further weathering, they gradually merge into alluvial fans. They are merely rock fragments, loosened as a result of weathering, that have rolled to the base of slopes or cliffs.

28. Water-formed Soils.—These are of the greatest agricultural importance chiefly because of the fact that, at some stage in the earth's history, water was a very important agent in the formation of all soils. There are, however, three classes of soils, based on their mode of deposition by direct water action.

(a) *Marine or sea-laid deposits.*—Such deposits are formed of sediment carried by streams and deposited in the sea, the coarser material being deposited near the shore, the finer particles at a distance. In soils of this character, the sands, sandy loams, and loams predominate. The soils of the Atlantic and Gulf coastal plains province **(75)** were formed in this manner.

(b) *Lacustrine or lake-laid deposits.*—These deposits consist primarily of terraces and beaches representing old water levels and the beds of ancient lakes that have long since disappeared. The glacial lake and river terrace province **(73)** was formed primarily in this way.

(c) *Alluvial or stream-laid deposits.*—Such soils consist of accumulations of water-borne sediment, deposited mainly as a

result of checking the stream's flow. These deposits are grouped (1) as flood-plain deposits, (2) as deltas, and (3) as alluvial fans, all of which may be found in stream-formed deposits as illustrated by the river flood-plains province **(76)**. The flood plains and alluvial fans, and to a less extent the deltas, may be deposited as terraces, or natural levees, forming levels of varying width and character. The terrace closest to the stream, and present flood plain, is usually called the first bottom; higher levels are called the second bottom or bench land.

Terraces may be formed by the deposition of material from overloaded streams, by the elevation of the surface of the earth, or by the ponding of tributary streams due to the building up of the flood plains of the main stream more rapidly than those of the tributaries. A delta is formed as a result of the stream flowing into a large stationary body of water, thus suddenly arresting its force. Alluvial fans are formed in much the same manner as deltas, except that rapid flowing streams, from mountains or plateaus, reach the lower levels and have their force checked. Deltas therefore are a continuation of the flood plain, but due to their location are difficult to drain. On the other hand, alluvial fan soils are often loose and porous to the point of droughtiness.

The water-formed soils are characterized by a more or less uniform topography and by deposits of gravel, sands, silts, clays, or mixtures of these.

29. Glacial Formations.—Soils formed as a result of glacial activities consist of the residual material (glacial drift) formed by the grinding action of ice and the carrying power of water. The material was apparently carried many miles. The effect of the glaciers was that of a great mill grinding large quantities of rock into powder. As the ice melted, this powder was distributed by the action of water and wind. The resulting material formed the basis of the productive glacial and loessal province **(102)**.

The general effect of the glaciers was to wear down hills, fill valleys, and make the areas more level. The leveling action was pronounced if the direction of the elevations was at right angles to the direction of the glacial drift. If the direction of the elevation happened to be the same as that of the glacier, the general tendency of the action was to deepen the valley. The drift left by the glaciers was usually unevenly but not abruptly distributed. The distribution depended upon the rate of melting taking place

at the face of the glacier. If the melting was faster or slower than the movement of the ice, the surface of the area was flattened out. If the melting was at the same rate as the movement of the ice, the débris was deposited in one area and a ridge or terminal moraine was formed. Such moraines may be several hundred feet in height and several miles long. The topography of large glaciated areas may be uniformly flat or may be more or less gently undulating or rolling.[3]

30. Loessal Formations are due mainly to wind activities. As the water flowed away from the glaciers, it carried away the rock flour, sand, and larger particles according to the force and intensity of the flow. The larger particles settled out quickly, but the smaller remained in suspension and were carried great distances or were left as dried mud when the water evaporated. If the water had been the only agency in the distribution of this soil, the topography of this portion of the glacial areas would possibly be uniformly flat. As a matter of fact, the topography of a great portion of the Missouri, Mississippi, and Ohio River valleys is rolling. The rolling is very pronounced on the eastern banks of the Mississippi River, almost to the Gulf of Mexico, and on the eastern banks of that portion of the Missouri River flowing almost due south. A careful study of the fine uniform character of the soil of these areas, of the wave-like contour of the hills, of the power of the wind to transport soils, has led to the conclusion that this agency is responsible for the greater part of the formation. Such soils are spoken of as "eolial" or wind-laid[4] soils and are commonly designated as loess.

There has been much controversy regarding the origin of loess. This soil is characterized by a light color, and by angular particles that are in an extremely fine state of subdivision. The material is in uniform deposits lacking stratification. While the deposits are very porous, the particles are quite coherent and not subject to weathering effects like other soils. For instance, the sides of a vertical cut through a deposit will remain in position, will even show the original marks of excavating tools, for years.

[3] For a popular description and illustration of glacial action and soil formation see Shaler, N. S., "The Origin and Nature of Soils," *12th Annual U. S. Geol. Survey Report, Part 1*, pp. 219-345. 1891.

[4] For a discussion of the influence of wind in soil formation, see Free, E. E., "The Movement of Soil Material by the Wind," *U. S. Dept. of Agric. Bur. of Soils Bul. 68.* 1911.

The general opinion is that the material is primarily the result of wind deposition, with water aiding or even being the primal factor in some cases. The theory of wind formation is strengthened by the fact that the fossil remains found in loess are almost without exception the remains of land animals, thus indicating that it possibly is not a deposit from permanent waters.

31. Kinds of Soil.—No matter how the soil material was placed or what agency was concerned in its formation, it was not, according to our definition, an agricultural soil. The material was in place, but needed to be acted upon by the various climatic factors of the area in question, needed to be influenced by the vegetation adapted to those climatic factors, and then gradually changed by natural processes from an inert inorganic mass to the live material as we know it. It is but natural that the material at the surface should be influenced to a greater extent by this combined climatic and plant action than the material at greater depths. Consequently we have various kinds of soil, each kind easily recognized by well-defined characteristics. For instance:

The surface soil.—This is frequently spoken of as the top soil, and is that familiar portion usually turned by the plow and subject to the various manipulations of farming. It is usually the arena of greatest soil activities, especially chemical and biological, and is the area occupied by the greatest amount of plant roots, due to its soil-derived plant-food content. It is darker in color, especially in the humid section, than the lower levels, due primarily to the organic matter content.

The subsurface.—The subsurface is that stratum lying between the surface and the subsoil extending from the plowline to where a change in color, physical composition, etc., indicates the beginning of the subsoil. It usually extends from 6 to 20 inches or more in depth.

The subsoil.—This soil extends to an indefinite depth, and usually is sampled for chemical and mechanical analysis to a depth of 40 to 60 inches.

The subsurface and the subsoil are of the greatest importance in plant growth because root penetration depends entirely upon their characteristics. Theirs is the area controlling primarily the moisture relationship of the soil and has a marked influence upon those physical, chemical, and biological functions affecting plant growth.

32. Characteristics of the Subsoil.—Due to the fact that the surface soil is at all times exposed to the full force of the agencies of weathering, it is continually subject to various changes that may have a marked effect on the underlying soil. Rains upon the surface wash down the finer particles or carry in solution materials that may be deposited at lower levels. Thus some areas are characterized by having a condition known as "tight clay," the direct result of washing down the finer particles to lower levels, or of "hard pan," the result of soluble material being carried down from the surface.

33. Organic Matter.—Heretofore the soil has been regarded mainly as a mineral complex constantly undergoing change. It undoubtedly existed in a purely mineral state during the earlier geologic eras, but during the latter eras this mineral complex has served as a source of nutrients and as a physical support for life forms. Apparently nature abhors a bare spot much as she does a vacuum. She endeavors to cover each exposed surface with some kind of plant life. In some cases, the plants may be microscopic, algae, etc. In others, they are of relatively gigantic proportion. The remains of all life forms, especially plants, have tended to accumulate in varying amounts in the upper soil levels. They are present in all stages of decomposition and of solubility. These remains, regardless of their origin or composition, form in the mineral complex a material classified as organic matter. This material imparts to the soil mass its life-giving properties and furnishes the necessary energy for most of the biologic and chemical functions. Organic matter causes the soil to be a dynamic complexity teeming with possibilities, instead of a dull static mass.

34. The Amount of Organic Matter in the Soil.—The amount of organic matter in the soil varies widely. Some soils—sands—may be practically devoid of organic carbon, while other soils—peats—may be practically pure organic matter. Most agricultural soils are in a group somewhere between these two extremes. It is calculated that the average organic matter[5] content of the soils of the United States is 2.06 per cent in the surface and 0.83 per cent in the subsoil. Some soil types are characterized by a high organic and others by a low organic

[5] Schreiner, O., and Shorey, E. C., "Chemical Nature of Soil Organic Matter," *U. S. Dept of Agric. Bur. of Soils Bul. 74.* 1910.

matter content. The amount in the soil is subject to great variation. It is easily reduced by tillage practices or may be increased by the addition of plant residues. If left alone, natural processes may or may not increase the organic matter content of the soil. Thus areas in grass may build up a high organic matter content (for instance, prairie soils). On the other hand, a forested area has very few tendencies, if any, in this direction.

35. The Condition of Soil Organic Matter.—While the organic matter commonly found in the soil has been derived from the tissues of plants and animals, it is distinctly different in composition from the original tissues because of the fact that it has been more or less completely utilized by the micro-biological soil population as a source of food. As a result, the soil organic matter is secondary in nature. It consists of the original tissues in all stages of decomposition. For instance, it consists first of the tissues that have been introduced into the soil and are undergoing decomposition; second, of various intermediary products which have been formed under certain environmental conditions and which may be decomposed further; and third, of substances which resist decomposition and which may persist for a considerable period. Further, the micro-biological population, in utilizing certain portions as food, synthesize and change the various compounds, building them up into various combinations that remain in the soil for various periods as living and dead cells and cell derivatives. The soil organic matter may be regarded as a heterogeneous mass of organic substances, of a gel-like nature, displaying marked colloidal properties and undergoing constant change.

36. Soil Plant Relationships.—The growth of plants is conditioned to a certain extent by the soil medium. Conversely the soil itself may be markedly affected by the amount and kind of vegetation growing upon it. The influence of the various soil conditions in the great soil areas upon crop growth is discussed in the following chapter. The distribution of the native vegetation covering these areas follows.

37. Native Vegetation of the United States.—Livingston and Shreve [6] state "as a law of plant geography, the existence, limits

[6] Livingston, B. E., and Shreve, F., "The Distribution of Vegetation in the United States as Related to Climatic Conditions," *Carnegie Inst. Wash. Pub. 284.* 1921. 590 pp.

and movements of plant communities are controlled by physical conditions. The conditions that control the movements of the community are those of the soil. The conditions that control the broader geographic limits are almost entirely those of climate." The soil, however, is in turn markedly affected by the kind of vegetative cover. The distribution of the native vegetation[7] is shown in Chart 5, Native Vegetation, page 342.

The vegetation ranges from the deciduous forests of the East to the sparse grasslands of the Great Plains, from the alpine meadows of the western mountain ranges to the subtropical forests of southern Florida, from the luxuriant forests of the Pacific northwest to the almost barren deserts of southeastern California. The total area of the United States (1,903,000,000 acres) may be divided on the basis of the original natural vegetation as follows:

Forests	
Hardwood forest	21 per cent
Coniferous forest	22 per cent
Woodland forest	5 per cent
Grassland	
Tall grass (prairie)	16 per cent
Short grass (plains)	14 per cent
Other grasses	8 per cent
Desert	
Northern desert (shrub)	10 per cent
Southern desert (shrub)	4 per cent

[7] The natural vegetation of the United States, as a physical basis of agriculture, is clearly illustrated by Shantz, H. L., and Zon, R., "Natural Vegetation," *Atlas of American Agriculture*, U. S. Dept. of Agric. Bur. of Agric. Economics, Advance Sheet 6, Part 1, Section E. 1924. 29 pp. They present a map, the details of which would be lost by reducing the size, illustrating the zones of twenty-eight groups of plant growth.

For further reference see:

Naturalist Guide to the Americas, ed. by V. E. Shelford; prepared by the Committee on the Preservation of Natural Conditions of the Ecological Society of America. Williams and Wilkins Co. Baltimore. Md. 761 pp. 1926.

Shantz, H. L., "Natural Vegetation as an Indicator of the Capability of Land for Crop Production in the Great Plains Area," *U. S. Dept. of Agric. Bur. Plant Ind. Bul. 201*. 1911.

Shantz, H. L., "The Natural Vegetation of the Great Plains Region," *Ann. Assoc. Am. Geo., 13*, pp. 81-107. 1923.

Clements, F. E., "Plant Indicators, the Relation of Plant Communities to Process and Practice," *Carnegie Inst. Wash. Pub. 290*. 1920.

CHAPTER 4

SOIL MORPHOLOGY

Soil morphology refers to the form, arrangement, and structural characteristics of the soil mass as it now exists. It includes the physical, chemical, and biological features, singly or combined, that lend themselves to examination and study. It may be divided into two groups: (1) the internal, and (2) the external characteristics of the soil mass.

38. The Soil Mass.—The soil mass may be looked upon as a complex system existing in four well-defined phases as follows:

I. The solid phase
1. The mineral particles of all sizes. The soil texture. Inorganic.
2. The residues of past generations of plants and animals. The organic matter.

II. The transitional phase: The colloidal state, transitional between solid and liquid phases.

III. The liquid phase
1. The soil water.
2. The soil solution.

IV. The gaseous phase: The soil air.

Each of these phases possesses certain properties and certain characteristics. It is evident, therefore, that the properties of the mass will be dependent upon the combined influences of the several functions and forces within it.

39. Internal Characteristics of the Soil Mass.—The internal morphological characteristics of the soil mass are mainly those features connected with the chemical and biological functions. They are the invisible functions that are continually changing. These functions are concerned mainly with the gaseous, liquid, and transitional phases, but markedly influence the condition of the solid phase. The addition of organic matter to the soil mass illustrates the changeable nature of the internal characteristics. When first added it is usually representative of the solid phase. It is decomposed and in the process passes through the other three phases. The results of decomposition may directly

or indirectly affect the whole mass, changing not only the internal (invisible) characteristics, but the external (visible) as well.

40. External Characteristics of the Soil Mass.—The external morphological characteristics of the soil mass is a result of genetic development. It is a combination of those visible features that give rise to the properties of the soil profile and the individual horizons. The external morphological characteristics of the soil profile form the main basis of soil classification. These characteristics have been studied in more or less detail and may be grouped under the following headings: (1) Soil color; (2) Soil structure; (3) Soil consistence; (4) Soil profile.

Soil Color

The natural color of a soil is usually one of the outstanding morphological characteristics upon which one bases his judgment of its potential productiveness. It is that feature which primarily attracts attention. Usually a black soil is regarded as rich and productive, while a white soil is regarded as poor and unproductive. This conception has arisen as a result of practical observation through the ages. The color of soils varies widely. One may observe a great diversity of shades, most of them belonging to the red or yellow part of the spectrum. Usually their color is not pronounced, but is characterized by soft or dull shades with their various tints.

41. General Conceptions of Color as Related to Productivity.—The following is a discussion of the general features of different colored soils [1] as related to productivity.

I. Dark-Colored Soils.—In the humid sections, when well drained and under favorable climatic conditions, black or brown soils are usually very productive. Their color is due mainly to the accumulation of decaying organic matter with the formation of humus. They are usually alluvial soils and are widely distributed, especially in and east of the Great Plains region. In many cases they are underlaid with calcareous subsoils. When excessively acid or when undrained, they are relatively unproductive. In the arid sections a greasy black soil, especially when occurring in black rings or spots, usually indicates the unfavorable condition of black alkali. In general, dark-colored soils are productive unless the color is locally associated with extremely

[1] Hilgard, E. W., *Soils*, p. 285. The Macmillan Co. New York, 1907.

fine texture, poor drainage conditions, or excessive amounts of soluble salts.

II. Red Soils.—The color of red soils is usually due to the presence of iron (**44, 2**), which may be in such amounts as to mask the presence of organic matter. Due to the fact that iron rust (ferric hydrate) cannot exist in poorly drained soils, also that finely diffused ferric hydrate has a high absorbing capacity for moisture, red-colored areas are usually well drained, are slow to suffer from drought, are not in need of large amounts of organic matter, hence are usually preferred.

III. Yellow Soils.—The yellow soils owe their color to either a smaller amount of iron than the red soils or to a difference in the composition of the iron (**44, 2**). Usually they are poorer drained than the red and are without sufficient organic matter to influence their color. Such soils are frequently quite acid and have a lowered crop-producing power. On the other hand, adobe soils, when irrigated, appear to have an inexhaustible ability to produce crops.

IV. Gray Soils.—East of the Great Plains, gray soils are usually, but not always, unproductive, due to the low humus and iron content. The 'crawfishy" soils of the East and South, with a water table close to the surface, are usually unproductive. On the other hand, there are areas of light gray soils in the Mississippi Valley that, when properly managed, are very productive. In the Great Plains region, the gray-colored soils are commonly those producing the greatest crop yields.

V. White Soils.—A white soil is to be regarded with suspicion. In the humid areas, a white soil usually indicates a sand or a compact clay. Usually the areas are small in extent and unproductive. In the semi-humid or arid regions a white soil usually indicates the present of alkali salts.

42. The Color of the Soil Particle.—The color of the soil particle is a result of those morphological features acquired during its genesis. The color of the predominating soil particles should be white due to the predominance of quartz. This, however, is not the case in Nature. It is true, as shown by strong acid digestion, etc., that the predominating color is white, but this is masked by the deposition of coloring matter (stains) on the surface of the particle, which in turn imparts certain color characteristics to the soil profile.

43. Color of the Soil Profile.—The profile (color profile) is characterized by variations or color strata in the different horizons. The soil mass in these horizons may, from the standpoint of color, be homogeneous (equally colored) or heterogeneous (unequally colored). In a specific horizon, the color may be uniform, variegated, or spotted. Variations are usually a result of a combination of factors; for instance, (1) the presence of varying amounts of coarse-textured particles; (2) additions, organic matter, etc., and (3) unequal removals from one portion and additions to another, through cracks, holes, etc.

44. Factors Affecting Soil Color.—The color of the soil is closely connected with its chemical composition and the different combination of the elements. These combinations may produce certain staining effects. A certain substance, for instance, the red or yellow of iron compounds, or the black of humus, may mask the lighter color of other materials or, conversely, may be masked according to the condition or preponderance of either. The relation of chemical composition, or chemical combination, and soil color may be grouped in descending order of importance as follows:

1. Organic matter (humus) **(225)** in large amounts imparts a black color; in small amounts, a gray. Alway and Blish[2] show a general relationship between the color changes and the percentage of humus determined colorimetrically, but not gravimetrically.

2. Iron compounds in large quantities impart a red or rusty color, in small amounts, a pink, orange or yellow color. Iron occurs in the form of two oxides—ferrous oxide, FeO, green colored; and ferric oxide, $Fe_2O_3\ n\ H_2O$, variously colored. As the ferrous salt rapidly oxidizes to the ferric condition it is rarely, if ever, a factor in soil color. The ferric oxide occurs in the following sesquioxides:

Limonite, $2Fe_2O_3 \cdot 3H_2O$ Yellow, brown
Xanthosiderite, $Fe_2O_3 \cdot 2H_2O$ Golden yellow brown
Goethite, $Fe_2O_3 \cdot H_2O$ Yellow, brown, brownish black
Turgite, $2Fe_2O_3 \cdot H_2O$ Red to reddish brown
Hematite, Fe_2O_3 Red

[2] Alway, F. J., and Blish, M. J., "The Loess Soils of the Nebraska Portion of the Transition Region II. Humus, Humus-Nitrogen, and Color," *Soil Science, 1*, pp. 239-258. 1916.

The members of this grouping differ from each other only in the amount of water, yet have a wide range of color variations. Dorsey [3] shows that the color of red rocks is not caused by a larger iron content than the non-red rocks, but is caused by ferric oxide which has had time to dehydrate and turn to the red hydrate (turgite) and the red anhydride (hematite). The dehydration apparently takes place most rapidly in warm moist climates.

Soil colorations due to iron are primarily a staining effect. That is, the surface of the soil particle is covered by a thin coat, hence the distribution of color is as important in influencing the general color effect as is the total amount of coloring matter present. MacCarthy [4] shows that quartz will become iron-stained only in the absence of more active absorbents, that orthoclase acquires iron stain more readily than quartz, and that while aluminum hydrate is a good adsorbent of iron, pure kaolin will adsorb but little unless activated by some substance as the alkali carbonates.

3. A high content of silicic acid, calcium carbonate, and kaolinite produces a white or whitish coloring of the soil.

4. Protoxides of iron occurring under superfluous moisture conditions and lack of aëration cause a bluish or dull grayish coloring of the soil. This is especially pronounced in the deeper soil horizon.

5. Oxides of manganese, if present in sufficient amounts, give an intensely black or brown coloration.

45. The Color of the Soil Mass.—The influences of the various factors of soil coloration are mutual. Combinations of color factors are the rule. As a consequence, the individual color factors of the above groups are superimposed on each other. This results in varying combinations and many intermediate shades of color in the soil mass.

Robinson and McCaughey [5] believe all soil masses are made up of varying amounts of materials having the three fundamental colors, white, black and red, represented by a white sand, a

[3] Dorsey, G. E., "The Origin of the Color of Red Beds," *Jour. of Geology*, *34*, pp. 131-144. 1926.

[4] MacCarthy, G. R., "Iron-Stained Sands and Clays," *Jour. of Geology*, *34*, pp. 352-360. 1926.

[5] Robinson, W. O., and McCaughey, "The Color of Soils," *U. S. Dept. of Agric. Bur. of Soils. Bul. 79*. 1911.

black muck and red ocher. Therefore, assuming the three fundamental colors as 100 per cent at the apices of an equilateral triangle, they believe (Fig. 1) the color of practically all soils is approximately determined by some point in the triangle. In other words, the color of the soil is assumed to be dependent upon the organic matter and iron content, and the thicker the film on the soil particle the darker the mass. Brown and O'Neal,[6] in studying the color of fourteen soil types, found no definite correlation between color and the carbon-nitrogen content, but secured indications showing a relation of color to organic matter content.

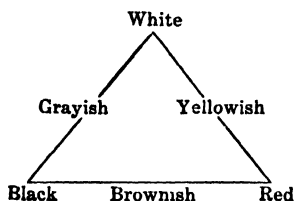



Fig. 1.

46. Defining Soil Color.—It is a well-known fact that the color of the soil mass is increased, up to a certain point, by increases of moisture content (dark-colored soils usually showing a greater change than light-colored soils), that soil particles react differently to the diffusion, absorption, refraction, and reflection of light, and that different persons have different ideas regarding the interpretation of colors. The designation of soil color is therefore dependent upon the individual. It is a result of local conditions and depends on: first, the stimulus (light), second, the sensing organs (the eyes), and third, a color vocabulary and definition of terms.[7] The latter has been practically met by the American Soil Survey Association's Committee on Color Standards,[8] which has adopted the following arbitrary list of thirty-two names for designating soil color:

1. White
2. Grayish white.
3. Light gray
4. Gray
5. Dark gray
6. Cream color
7. Light grayish yellow
8. Yellow
9. Orange
10. Yellowish brown
11. Brown
12. Light reddish brown

[6] Brown, P. E., and O'Neal, A. M., Jr., "The Color of Soils in Relation to Organic Matter Content," *Iowa Agric. Expt. Sta. Resch. Bul.* 75. 1923.

[7] Bushnell, T. M., "Vocabulary of Soil Color Terms," *Amer. Soil Survey Assoc. Rept. Bul.* 7, pp. 93-96. 1926.

[8] See Amer. Soil Survey Assoc. Rept. *Bul. 4*, Vol. 2, pp. 89-95. 1923. *Bul. 6*, Vol. 2, pp. 88-90. 1924. *Bul.* 7, Vol. 1, pp. 92-96. 1926. *Bul.* 8, pp. 53-56. 1927 *Bul.* 9, pp. 139-140a. 1928.

13. Reddish brown
14. Dark brown
15. Dark grayish brown
16. Very dark brown
17. Very dark grayish brown
18. Black
19. Olive gray
20. Dark olive gray
21. Mouse gray
22. Yellowish olive
23. Dark olive drab
24. Light reddish yellow
25. Yellowish red
26. Red
27. Deep red
28. Dark red
29. Dark brownish red
30. Purplish brown
31. Grayish purple
32. Purplish red

47. The Interpretation of Soil Color.—The exact designation of the color of a soil is by no means an easy matter. The soil horizons in humid regions, particularly the lower ones, are usually variegated in color: that is, the predominating color is spotted, streaked, or marked with areas of varying size and regularity having a different color. The term "mottled" is used to describe the phases of this condition, but the exact interpretation is difficult. For instance, a gray substratum spotted with yellow may grade into a yellow substratum spotted with gray. The color of moist soils is usually quite different from that of dry. Further, the color of a freshly broken face may be changed by lightly rubbing it. Or the color of an area at one period of the year may be slightly different at another period. All of which leads to the conclusion that the accurate determination of the color is a highly difficult matter and its interpretation is mainly a result of experience.

48. Color Changes in the Soil.—It is a well-known fact that the color of the surface is usually (especially in humid areas) quite different from that of the subsoil. The tendency in the northern sections of the United States east of the Great Plains is for the surface to be darker in color than the underlying horizon, while in the southern sections the reverse may be true. In the regions of limited rainfall, the color changes are usually less pronounced, while the color of similar soils in areas of high and low altitudes may be quite different.[9] Whatever the color of the original surface mass, it is usually changed to a greater or less extent by tillage. Thus a peat soil, when first placed under

[9] Crosby, W. O., "On the Contrast of Color of the Soils of High and Low Latitudes," *American Geologist*, 8, pp. 72-82. 1891.

cultivation, may be brown or red, in a few seasons turning to a very dark grayish brown or black. High organic matter (dark colored) soils, when tilled for long periods without means for keeping up the organic matter content, become lighter, taking on brownish, yellowish, or reddish shades. Soils having a poor air content, undrained, impervious clays, etc., may be black, blue, gray, mottled, or white; and, when the condition is improved by drainage or otherwise, may change their color to various shades of red, yellow, or brown. Light-colored soils may be darkened by an increase of their organic matter content.

49. The Importance of Soil Color.—The exact relation between color of soils and their crop-producing power has never been determined. It is generally assumed, however, that the color is a direct indication of the temperature, air, and moisture relationship; that these in turn have an important bearing on the physical, chemical, and biological functions of the soil, especially as related to the ability of the soil to support plant growth.

Soil Structure

The soil may be likened to a building; that is, its genesis has resulted in the particles being fashioned together in a definite manner. The arrangement of the individual grains and aggregates that make up the soil mass is spoken of as the soil structure. The term soil structure may refer to the natural arrangement of the soil when in place and undisturbed, or of the soil at any degree of disturbance.

The structure of the soil is of great importance in crop production. Plant roots require a certain admixture of air and water for their best growth. This requirement cannot be met entirely on the basis of textural composition, but is dependent also on the physical characteristics of the particles and their arrangement to form certain conditions that may bring about the desired results.

50. Conditions of Soil Structure.—The structural capacity of the soil mass depends upon a minimum content of cementing colloids, both organic and inorganic. In other words, structure is a function of the mass that enables certain particles to group themselves into aggregates. To a certain degree, structure is a property of soil consistence. The soil mass may be deficient in

structure (structureless) when it is without any discernible aggregation, or it may possess very marked structural characteristics. The different conditions may be due to the presence or absence of certain electrolytes or to variation in chemical composition, temperature, or moisture. For instance, a sandy soil may be structureless due to the absence of colloids, or a clay soil may, under certain conditions, be structureless due to the absence of substances capable of coagulating the colloids. An admixture of sand and clay, however, usually results in certain structural characteristics.

51. Structural Characteristics.—The grouping of soil particles into aggregates resembles somewhat the character of crystals. That is, they tend to form "planes of cleavage or of fracture." The aggregates, at their mutual intersection, form either acute or oblique and rounded edges. The faces of the aggregates may be more or less clearly defined.[10]

52. Structural Profile.—It rarely happens that all the soil aggregates, even within the limits of a given horizon, are of equal shape and size. Usually there is a combination of structural features. The difference in structure becomes more marked with increase in depth; for instance, the majority of soil profiles are structureless at the surface, but possess a very definite structure at lower depths.

53. Conditions Affecting Soil Structure.—The ability of the soil mass to maintain its structural profile is mainly a result of (1) the colloidal content, (2) the organic matter content, and (3) the moisture content of the mass.

1. The colloidal content, due to its internal surface area and the tendency to form, in the colloidal state, a gelatinous condition, exerts a cementing effect on the particles of the mass. The degree of cementation is dependent upon the amount and kind of colloidal material, the presence or absence of electrolytes, the amount of moisture, and of organic matter.

2. The natural or artificial introduction of organic matter into the soil mass exerts a mechanical effect of holding the aggregates apart. When the material decomposes, the channels thus formed may persist for some time. The organic matter itself increases the volume of the soil mass, while its effects of separating the

[10] For the different structural terms in general use and their definition, the student is urged to consult *Soil structure* in the Glossary.

aggregates gives a greater freedom for air and water movements. In many cases, the channels formed as a result of decomposition (or by animal activities) serve as tubes for conducting materials from upper to lower horizons.

3. The moisture content of the mass has a greater effect on soil consistence than it has on soil structure. Yet the development of the structural profile has possibly been due more to the sorting effects of water than to any one other factor.

Soil Consistence

Soil consistence is a term expressing the degree of cohesion of the soil particles and the resistance offered to forces tending to deform or rupture the aggregates. It refers to the tenacity of the structural aggregates. The structural property of the soil mass (hard pan formation, etc.) may be such as to give an equal tenacity when in either the moist or the dry condition. Usually the aggregates possess a more or less definite tenacity when dry or slightly moist, but are deprived of this property when wet. In some cases, soils may exhibit a certain consistence in the moist state, but when dry fall to pieces.

54. Tenacity of Structure.—The structural elements of the soil mass exhibit different properties when placed in water. They may be, first, completely dissociated into individual particles; second, incompletely dissociated, only certain portions falling apart while others retain, to a greater or lesser degree, their original structure; and third, they may not be affected. Thus the tenacity of the structure may not be apparent or it may be strongly evidenced. Due to the fact that the material removed from the A horizon (the surface soil) may be deposited in the B horizon (the subsoil), there is a tendency for the degree of tenacity to increase with increases in soil depth.

The Soil Profile

The characteristics of the soil profile are the result of soil genesis. These characteristics reproduce to a certain extent the complicated and subtle processes by which the soil is being formed. The profile is a sequence of horizons. A general aspect offered to the observer by a vertical section of the soil from the surface to the underlying unweathered material. A soil column. "It is an expression connoting the number, character, and succes-

sion of the several layers of material encountered in examining a vertical section of the soil from the surface to a depth of several feet, usually somewhat less than ten."

55. The Soil Horizons.—The soil mass is not homogeneous throughout its depth. Its variations are mainly due to climatic influences. The effect of rain water is to destroy the crumb-structure, to wash out soluble salts, and to peptonize the soil colloid. This water percolating through the soil and carrying soluble and suspended material encounters either chemical or physical conditions that result in a precipitating or filtering effect and the formation of layers of varying degrees of density and thickness. The various layers are grouped into horizons as follows:

I. Horizon A.—The upper or A horizon is the area of extraction from which material has been moved to the lower levels. The horizon of eluviation. The "surface" soil. It is usually coarser in texture than the lower horizons, while its structural and consistency characteristics are not so well defined. It is the area containing the largest amount of organic matter and usually the smallest amount of colloidal material. This horizon is generally subdivided into two or more sub-horizons, of which A_0 is not a part of the mineral soil, but is the accumulation of organic matter upon the soil surface. Other sub-horizons are designated in descending order of depth, as A_1, A_2, etc.

II. Horizon B.—The lower or B horizon is the horizon of deposition or concentration to which materials have been added from above. The horizon of illuviation. The "subsoil." It may be regarded as transitional in nature, differing in color, structure, and consistency from the upper A horizon and more or less gradually assimilating with the C horizon below. Usually its structural characteristics are well defined. It usually exhibits marked properties of consistency. It also may be divided into sub-horizons designated as B_1, B_2, etc.

III. Horizon C.—The horizon of unweathered material underlying the B horizon. The "substratum." It is featured by its geological characteristics. It may consist of consolidated rock, disintegrated rock, or unconsolidated accumulations showing features at variance with the B horizon. The C horizon, while considered as unweathered, usually shows some modification in the upper portions and may have one or more sub-horizons. In most

cases, it represents the "parent material" similar to that from which the soil was formed. In some cases, it may be a stratum of geological formation of different material. Its sub-horizons are differentiated mainly on the basis of the extent of leaching, i.e. the C_1 horizon may be leached of such carbonates as the parent geological material may have originally contained, while the C_2 may not have been changed.

56. Climate and the Soil Horizon.—The effect of climate on the development of soil horizons is marked. Salter[11] lists the following factors as favoring the rapid development of the different horizons:

A climate such that the soil remains for long periods at temperatures slightly above freezing, with considerable rainfall during these periods. Of less importance would be the lack of deep freezing and the absence of its temporary flocculating effects.

A fine-textured parent material or one which weathers rapidly with the formation of considerable material of colloidal dimensions, especially of colloidal clay.

The absence of alkaline earth carbonates both in surface and alluvial layers, either by reason of a non-calcareous parent material or through removal by leaching. (The alluvial layer is often underlaid by a calcareous layer.)

A level topography, causing a relatively large part of the precipitation to penetrate the soil.

A more or less permanent water table at a sufficient depth below the surface not to interfere with the downward percolation of water and yet high enough to prevent flocculation in subsoil due to drying.

57. Profile Characteristics in the United States.—As the profile has been developed under a variety of conditions, it would naturally exhibit a wide divergency of types. Marbut[12] groups

[11] Salter, R. M., "Climatic Agencies in Their Relation to Soil Colloids," *Jour. Amer. Soc. Agron.*, *17*, pp. 294-307. 1925.

[12] Marbut, C. F., "Soil Classification," *Amer. Soil Survey Assoc. Rept. Bul. 3*, pp. 24-32. 1922. In 1913 Marbut *et al* published a map, Chart No. 8, pp. 344-5, dividing the United States into thirteen soil areas, based mainly on soil genesis. This was followed in 1921 by a map, Chart No. 6, page 343, in which the divisions are based mainly on soil color. Later a series of maps are presented in which the soil areas of the United States are divided according to a world-wide scheme of soil classification. See Marbut, C. F., "A Scheme for Soil Classification," *Proc. First International Congress of Soil Science*, Washington, D. C. Commission V and VI, pp. 1-31. 1928.

the soil profiles of that part of the United States east of the Rocky Mountains into ten groups. The outline map, Fig. 2, shows the

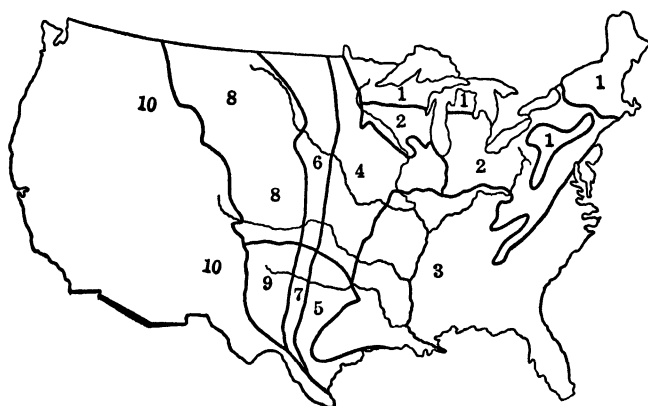



FIG. 2—Profile characteristics in the United States (From Marbut, *Soil Classification*.)

general area in which each of these profiles is predominantly characteristic of the mature soil. The grouping follows:

Profile 1.

1. Forest débris; rohhumus, trockentorf. As a rule it rests directly on the soil with a very thin layer, or no layer at all, of decomposed organic matter (mull) at the bottom.
2. Gray horizon, ranging in thickness from a film in very heavy soils to several inches in thickness. The podsolized horizon.
3. Chocolate brown, coffee brown, rusty brown horizon. The orterde or ortstein horizon. In some cases may be indurated. May range up to twelve inches in thickness.
4. Partially weathered parent soil material. No sharp line between this and No. 3.

Profile 2.

1. Forest débris consisting of leaves at the surface and the forest mold or mull below, usually mixed with dark-colored earth due to the work of worms and insects.
2. Dark brown horizon, consisting of brown mineral soil material mixed with forest mold. Ranges up to three or four inches.
3. Brown horizon often with yellowish shade, ranges up to eighteen inches in the medium-textured soils and deeper in sands.

4. Reddish brown to yellowish brown horizon, heavier than any of the overlying horizons; the reddish brown shade being more common in the lighter-textured members.

5. Parent material usually partially weathered at the top.

Profile 3.

1. Forest mold with mull horizon as in No. 2, but both mold and mull usually thinner than in the latter.

2. Dark gray horizon, consisting of light-colored mineral soil material mixed with forest mold.

3. Pale yellow to yellow horizon ranging up to about eighteen inches in the medium-textured types.

4. Brownish yellow to yellow horizon, heavier than No. 3, extends to depths of several feet.

5. Reddish horizon, mottled throughout or only in lower part.

6. Parent soil material.

Profile 4.

1. Dark brown to black horizon, filled with grass roots but usually little or no accumulation of mold on the surface. Lower part of horizon becomes browner through decrease of organic matter. Ranges up to fifteen inches.

2. Brown to yellowish brown horizon which is usually similar to No. 1 in texture.

3. Brown horizon, heavier than higher horizons. Ranges up to three feet or more in thickness.

4. Parent soil material partially weathered.

Profile 5.

Similar to No. 4, being less dark in color of the surface horizon and having a reddish brown horizon 3. Depth to the parent material somewhat greater than in No. 4 when other conditions are equal.

Profile 6.

1. Black horizon, usually with no surface accumulation of undecomposed organic matter. Soil filled with grass roots. Ranges in depth up to fifteen inches.

2. Yellowish brown to brown horizon, ranges up to three feet in thickness.

3. Yellowish brown to greenish brown or greenish yellow hori-

zon filled with streaks and spots of gray lime carbonate. Ranges up to three feet or more in thickness.

4. Parent soil material.

Profile 7.

Somewhat similar to No. 6, differing from it in the dark chocolate brown soil and the pinkish to reddish color and usualty higher carbonate concentration of horizon 3. Horizon 2 is usually reddish also.

Profile 8.

1. Chestnut brown to dark brown horizon. No accumulation of undecomposed organic matter on the surface. Soil filled with grass roots. Ranges up to about ten inches in thickness.
2. Yellowish brown horizon, usually a few inches in thickness.
3. Carbonate horizon, usually enough carbonate to color whole horizon gray. Ranges up to two feet in thickness.
4. Parent material.

Profile 9.

Similar to No. 8 but redder brown in the surface soil and pinkish or reddish in the subsoil.

Profile 10.

1. Brown horizon.
2. Thin lighter brown horizon, often absent.
3. Calcareous zone.
4. Parent material.

58. Characteristics of the Soil Profile.[13]—The condition of the several horizons is shown by a study of a mature soil profile. The variations in color and characteristics are shown in Fig. 3.

The variations in the physical properties of the Miami silt loam, shown in Figure 3, are given in Table 1.

59. Conditions Affecting the Soil Profile.—Any condition or circumstance affecting soil genesis is reflected in the profile. The action of plants and animals, moving or forming holes in the mass, may markedly alter the profile characteristics. Their remains may induce color changes. The conditions under which

[13] Hawkins, A. H., "Soil Cross Sections," *Amer. Soil Survey Assoc. Rept. Bul. 5*, pp. 160-169. 1925.

Wheeting, L. C., "Some Physical and Chemical Properties of Several Soil Profiles," *Mich. Agric. Expt. Sta. Tech. Bul. 62*. 1924.

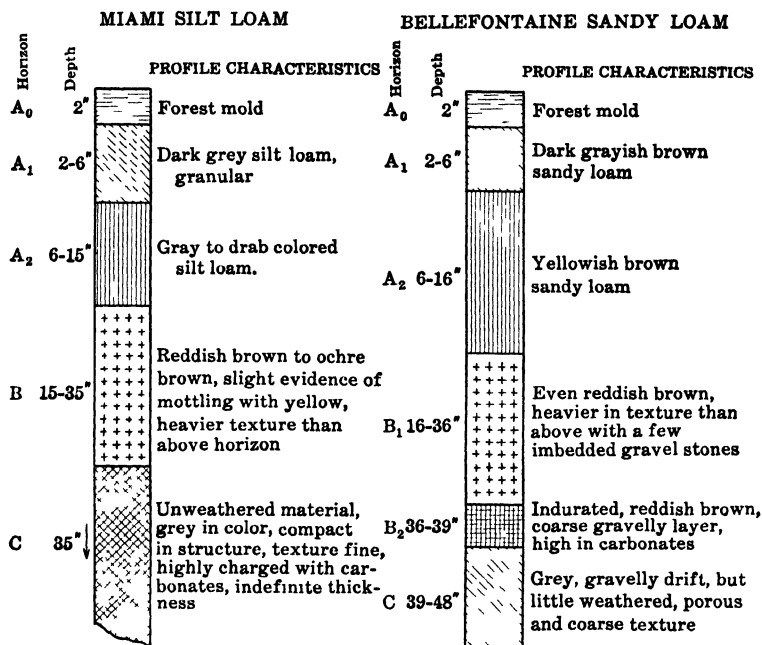



FIG. 3.—Profile characteristics of two soil types (Adapted from *Mich Agric. Expt. Sta. Tech Bul 62*)

the various horizons have been developed are favorable to changes, consequently there is a marked variation in thickness. The action of water in moving and concentrating materials may result, first, in a uniform distribution throughout the B horizon;

TABLE 1

SOME PHYSICAL CHARACTERISTICS OF MIAMI SILT LOAM HORIZONS

HORIZON	PARTIAL MECHANICAL ANALYSIS %				WATER, PER CENT				
	Coarse Sand	Fine Sand	Silt	Clay	Free †	Cap. Absorbed *	Combined §	Hygroscopic	Heat of Wetting ‡
A 1 .	4 879	27.528	37 127	7.446	9 0	1 20	9.80	1.702	87.11
A 2 .	2 708	22.170	33.131	7.847	15.1	1.05	3 85	0 520	26 83
B . .	3 019	19.399	24.970	22.400	11.1	1 30	7.60	1.391	64.72
C 1 .	1.234	5 280	54.575	25.727	7.2	2.75	10.00	1.264	61.80

† Water that freezes at —1 5°C.
* Water that freezes between — 1 5° and —4 0°C.
§ Water that will not freeze
‡ Calories evolved by 25 grams of soil.

second, in an accumulation in a definite horizon, or third, in local accumulations. The latter may be identified by stained areas or even by the presence of nodules or concretions of various sizes and kinds. In some cases, the upward movement of water may carry a deposit of salts to certain levels or to the surface.

CHAPTER 5

SOIL CLASSIFICATION

The development of science apparently keeps pace with the development of man. No scientific achievement is of value unless it has some use. During the earlier stages of man, the developments were along practical lines, tending toward the utilization of nature. During the later stages, man has continued the utilitarian viewpoint and also has endeavored to acquire abstract knowledge of nature and discover the laws of phenomena. At the present time, the latter endeavor is in the ascendency.

From the earliest times, soil areas have been divided or classified according to their crop-producing powers or according to the more or less valuable products which they were capable of yielding. These areas were further subdivided according to their adaptability to certain plants; for instance, rich wheat soils, cold oat soils, etc. Such classifications sufficed for centuries. It was not until the beginning of the nineteenth century that, in conjunction with other lines of scientific development, curiosity was manifested among the more thoughtful, regarding the characteristics of the soil, and it was not until the beginning of the twentieth century that the great body of facts and principles universally recognized as pertaining to the subject became apparent.

60. Soil Classification in General.—Coffey [1] states, "There is probably no line of agricultural work which has had a more rapid development and extension within the last decade than the classifying and mapping of soils." He shows that the earlier soils work was conducted primarily by geologists and that their influence has had much to do with the general acceptance of the geological system of classification. As a result of this condition, there has been considerable confusion in agronomic literature regarding soil classification. This confusion is not due to a lack

[1] Coffey, G. N., "The Development of Soil Survey Work in the United States with a Brief Reference to Foreign Countries," *Jour. Amer. Soc. Agron.*, *3*, pp. 115-129. 1911.

of understanding of soil conditions and characteristics; rather it is due to an attempt to derive a satisfactory classification based upon some principle, for instance geologic, or combination of principles that is known to be scientifically correct. In other words, an attempt has been made to classify soil on the basis of laws derived from sources outside, but closely akin to the soil itself. It is but natural that scientists have used certain extensive and predominating features as a basis for classification. Or, viewed in another light, certain features of soil genesis have been intensified while others have been reduced.

61. Grouping of Soil Classifications.—Tulaikoff[2] groups the existing classifications under the following headings:

I. "The Geologico-Petrographical.—In this classification the soils are grouped according to the geologico-petrographical character of the rocks which make up the soil."

II. "The Chemical or Chemico-Petrographical.—Soils classified according to the main chemical features of the soil."

III. "The Physical.—Soils classified according to the mechanical composition and the physical characteristics derived from it."

IV. "The Combined Classifications.—A combination of factors by which soils are divided into groups, for example according to their mechanical composition, and subdivided according to either their chemical composition or other features."

V. "The Genetic.—The basis of this classification is that soils are divided into groups depending on their origin and development."

These classifications were developed primarily in Germany, Russia, and the United States. Their number indicates the trend of scientific soil investigations, their wide viewpoint indicates the

[2] Tulaikoff, N. M., "The Genetic Classification of Soils," *Jour. Agric. Science, 3*, pp. 80-85. 1908.

For general reference on classification see Glinka, K., translated by Marbut, C. F., *The Great Soil Groups of the World.* Mimeographed 1927, Edwards Bros., Ann Arbor, Mich. Raman, E., Translated by Whittles, C. L., *The Evolution and Classification of Soils.* W. Heffer & Sons, Cambridge, 1928. 118 pp. Also the series of papers appearing in the *Proceedings of the First International Congress of Soil Science*, Commission V. Washington, D. C., 1928.

For a discussion of tropical soils see Shantz, H. L., and Marbut, C. F., "The Vegetation and Soils of Africa," *American Geographic Society, Research Series 13*, 1923. Clarke, F. W., "Data of Geochemistry," *U. S. Geol. Sur. Bul. 770*, p. 496. Bennett, H. H., and Allison, R. V., *The Soils of Cuba*, Tropical Plant Research Foundation, Washington, D. C., 1928. 410 pp.

possibility of a common basis for deriving an acceptable world-wide classification. Such a basis apparently lies in the morphological characteristics of the mass *in situ*.

62. Schools of Soil Investigation and Classification.—It is natural that an acceptable basis of soil classification should include all morphological characteristics. Earlier workers were not aware of the extreme complexity of the soil mass under all conditions. They consequently suggested classifications based on the knowledge of the time. Further, the efforts of earlier workers to produce satisfactory world-wide classifications were hampered by the boundaries of their own countries or by an insufficient knowledge of details. Classifications suggested for small areas failed when applied to larger areas. As a consequence, those countries interested in soils and having the greatest areas naturally took the lead. This resulted in the development of two independent schools of soil science, the Russian and the American. Both of these were founded in part on certain soil principles developed by the German school of scientists.

I. The German School.—The German school was developed primarily by the contributions of Thaer, Kallou, Knop, Baron von Richthofen, and Walther. It was founded by men interested in soils from the geologico-petrographical viewpoint. The viewpoint may be expressed in the words of Richthofen, who considered soil to be "the product of physical processes which are, on one hand, determined by climate, by the relief of the earth's surface and by the properties of the parent rock, and on the other hand, by the oscillations of land and sea, and by the transfer of solid masses."

II. The Russian School.—The Russian school was developed primarily by Dokuchaiev and Sibirtsev. These men were not so much interested in the problem of grouping soils which are concretely known as they were in finding a general theoretical solution for the classification problem. They endeavored to establish the basic laws of soil genesis, the laws which create the infinite variety of soils and by which their geography is governed. They emphasized the relationship of climate to soil formation and classification. Soil formation was viewed as a function of the following genetic factors: (1) the nature of the parent rock, (2) the climate of the locality, (3) the mass and character of vegetation, (4) the age of the country, and (5) the relief of the

locality. In 1914 Glinka first made available to the world at large the Russian idea of the gradating effects of climate and moisture on soil development.

As a result of the advancement of the theories of soil acidity, of colloidal chemistry, the importance and rôle of soil colloids, and the development of the soil complex, Gedroiz in 1925 brought out the importance of the chemical applications to soil classification, basing his proposed classification on the nature of the cations found in the absorptive complex

III The American School began in 1894 with the formation of the Agricultural Soils Division as a branch of the United States Weather Bureau It was headed by Dr Milton Whitney In 1901 the Bureau of Soils was formed The Bureau began its studies with the soil in detail Problems of mapping, soil surveying, and classification were headed by Dr C F Marbut The results of the Russian investigators were not available because of the language in which they were preserved The investigations of the two schools were therefore developed independently The classificational problems of the United States Bureau of Soils were concerned at first mainly with details of geographic conception (the development of the soil provinces and regions), accompanied with certain ideas as to details of soil character and methods of presenting to the public in general No definite system of classification has been advanced by this school, rather the idea has been to develop the scientific principles and at the same time adapt them to agricultural problems

63. The Present Status of Soil Classification.—It may be said that the whole matter of soil classification at the present time is in the formative stage No group of soil scientists have come to any final agreement regarding their problems Soil specialists [3] are convinced that any soil classification that will meet what may be called world-wide demands must be based upon the characteristic features of the soil, rather than on a series of causes, assumed, with or without reason for such assumption, to have produced these characteristics This can only be accom-

[3] At a meeting of the Fourth Committee of the International Society of Soil Science (Pedology) Rome 1924 the following recommendation was adopted That the Committee recommend to all persons in all countries the study of *soil profiles* and the accumulation of as much data as possible on the subject to the end that a scheme of soil classification, based on these features may be devised

plished by defining and accurately describing the vertical section of the soil or *the soil profile.*

64. The System of the United States Bureau of Soils.—The classification of soils as adopted by the United States Bureau of Soils is in reality an adaptation and combination of those features of previous classifications which have been found to apply to the characteristic features of the soils (*in situ*) of the entire United States. It recognizes the geological, physical, chemical, and genetic characteristics of the soil profile. The United States Bureau of Soils classifies areas on the basis of (1) the soil region or the soil province; (2) the soil series; (3) the soil class; and (4) the soil type.[1] The unit of classification is the type. The type name consists of two or more words. The first word is the series name; the second is the class name (Webster loam). When there are more than two words, the additional words are explanatory and may be in relation to texture (Susquehanna fine sandy loam), or in relation to certain physiographic characteristics (Tama loam, rolling phase), etc. The series is a characteristic of, and the name is used only in, a certain region or province. The class is characteristic of all areas. A certain type can only occur in a certain region or province. It is not limited to a definite and continuous area but may occur in many isolated areas, distributed over a larger division.

65. Naming the Type.—Naming or designating a soil type is a painstaking operation and is the result of a careful study and correlation of many characteristic profiles over an extended area. The type is named as a result of coöperative field and laboratory work, and correlated by competent individuals. The field work is done by the soil surveyor who takes a census of the soil characteristics of the area. He notes in general the formation and origin of the soil, its topographic and geographic features, its drainage systems, and its agricultural relationships. He studies in detail the structure, texture, and consistence of the soil profile, taking careful notes of color changes, physical composition, and other details that may become important. The laboratory work consists of mechanical and chemical analyses. The mechanical analyses are used mainly as a basis for the class separation, the chemical being used as an indication of the agricultural value,

[1] It is important that the Glossary of Terms be consulted for definition and clarity.

origin, formation, etc. The field and laboratory results are correlated by inspectors from the Bureau of Soils, aided by the surveyor and possibly others. Thus by coöperation, the characteristics and limitations of the type are defined and described in such a manner that, as far as possible, the type will be recognizable—at least by competent individuals, when again encountered in the field. While it is a comparatively simple matter to define the characteristic type of a certain area, the differentiation of closely related types and the location of the border line becomes extremely difficult.

66. The Detailed Soil Survey.[5]—A detailed soil survey of any area (usually a certain county of a state) consists of:

First, the preparation of an accurate base map; second, the determination of the different soils series within this area; third, the identification of the various classes and types of soil by a close study of the field samples and marking the borders of the various types upon the map; and fourth, the preparation of an accurate soils map showing the position of all types,[6] and a report of the agricultural conditions.

67. Publications of the Soil Survey.—The reports of the Soil Survey in the United States are first published by the United States Bureau of Soils as a soil survey report of the individual county. These reports contain a description of the general characteristics of the county, a soil map of the area, detailed descriptions of the various types of soil found, with mechanical analyses of some of the major types. In some states, this report is later followed by an experiment station report, repeating much of the detail of the government report, and including such additional features as a chemical analysis, results of pot and field experiments, and general recommendations regarding the crop adaptation and soil management of the several soil types.

In England, the reports are published mainly in the *Journal of Agricultural Science*. In France, the work is particularly

[5] Emerson, P., *Soil Characteristics*, p. 9. McGraw-Hill Book Company. New York, 1925. 222 pp.
See also "What Information Is Necessary for a Complete Description of a Soil." Krusekopf, H. H., "A. Field Aspects." Bradfield, R., "B. Laboratory Aspects." *Amer. Soil Survey Assn. Rept. Bul.* 8, pp. 98-111. 1927.

[6] At the present time, 1927, a few states have completed their detailed survey, while the majority are rapidly pushing the work to completion. For the "Status of the Soil Survey by States," year ending June 30, 1925, see *Yearbook U. S. Dept. of Agric.*, p. 1448. 1925.

associated with the Station Agronomique de l'Aisne et Laon. In Germany, the publications are chiefly in the *Int. Mitt. Bodenkunde.*

68. The Utilization of the Soil Survey.—In a symposium [7] on "The Utilization of the Soil Survey" the important facts were brought out that the soil survey reports were being used by persons or organizations interested in a variety of phases of agricultural and rural conditions. They were being used by the farmers as a guide to the production of better crops; by loan organizations as a basis of land value; by public officials as a basis for public improvements, drainage, roads, etc.; by people looking for land as prospective settlers; by organizations seeking to locate enterprises connected with agriculture, warehouses, canning factories, etc.; by scientists in the investigation of soil phenomena; by instructors as a basis of increasing soil knowledge; by plant specialists as a basis for the introduction of new crops or the improvement of crops; by county organizations as a basis for advertising their areas by presenting a picture of the area in the form of a map and giving detailed and unbiased descriptions of its resources; by the extension worker in providing definite information demanded or needed by the rural population; and in many other ways aiding agricultural and soil knowledge.

69. Soil Classification and Land Valuation.—While the soil survey gives an accurate picture of the conditions above, at the surface, and underneath the area, it cannot do more than give a relative idea of the value of the soil. The market value of land is

[7] Whitney, M. D., "The Future of the Soil Survey in Our National Agricultural Policy," *Jour. Amer. Soc. of Agron.*, *16*, pp. 409-412. 1924.

Whitson, A. R., "Difficulties in Utilizing the Work of the Soil Survey," *ibid.*, *16*, pp. 413-416. 1924.

Rice, T. D., "The Relation of the Soil Survey to the Settlement of Unused Lands," *ibid.*, *16*, pp. 416-421. 1924.

Bennet, H. H., "The Relation of the Soils Survey to the Utilization of Southern Soils," *ibid.*, *16*, pp. 421-428. 1924.

"The Value of the Soil Survey as a Basis for Soil Studies and Soil Use": (*a*) McCool, M. M., "In Study of Soil Properties," *ibid.*, *16*, pp. 429-432. 1924. (*b*) DeTurk, E. E., "In Experimental Work in Soil Management and Uses," *ibid.*, *16*, pp. 433-437. 1924. (*c*) Bear, F. E., "In the Teaching of Soils in College, *ibid.*, *16*, pp. 437-439. 1924.

"The Utilization of the Soil Survey in Crop Experimental Work"—Discussion by Burlison, W. L., and Mooers, C. A., *ibid.*, *16*, pp. 440-447.

Williams, C. B., "How the Soil Survey Is Proving Most Valuable in North Carolina," *ibid.*, *16*, pp. 447-451, 1924.

Morgan, M. F., "Land Cover Studies as a Basis for a More Accurate Interpretation of the Soil Survey," *ibid.*, *16*, pp. 452-458, 1924.

determined by its productive capacity for different crops and by its relation to the community at large. The productive capacity is dependent mainly upon the climatic factor, the topography, the plant-food content of the soil, its reaction, texture, supply of organic matter, drainage, moisture supply, character of subsoil, and adaptation to general or specific crops. When one examines an area with the idea of buying it, he should be able to determine these factors with reasonable accuracy in the field or by consulting the natives. These factors may be studied by the use of a score card. The form of such a card is given by Miller [8] as follows:

SCORE CARD FOR JUDGING FARM LANDS

Texture (fine, medium, or coarse)......................	10	points
Character of subsoil (fine, medium, or coarse texture, loose or compact)......................	10	"
Depth of surface soil......................	15	"
Topography (as influencing erosion, drainage, and ease of handling)......................	15	"
Color of soil (black, brown, red, gray, as indicating productivity)......................	15	"
Nature of wild and crop growth (as indicating productivity)	10	"
Test for acidity (the score of acid soils should be reduced according to the degree of acidity)......................	10	"
Present stage of fertility as influenced by past management (as shown by the land itself and by its history)......	15	"

A more detailed form illustrating the points to be observed when a person is selecting a farm is given by Thomson.[9]

[8] Miller, M. F., *The Soil and Its Management*, p. 156. Ginn and Company. New York. 1924. 386 pp.

[9] Thomson, E. H., "Selecting a Farm, *U. S. Dept. of Agric. Farmers Bulletin 1088*, p. 25. 1920.

For further reference see:

Miller, M. F., *et al.*, "Land Valuation," *Missouri Agric. Expt. Sta. Bul. 255*. 1927.

Henderson, B., "Buying a Farm in an Undeveloped Region," *U. S. Dept. of Agric. Farmers Bulletin 1385*. 1924.

CHAPTER 6

SOIL AREAS OF THE UNITED STATES

It is but natural that, in an area as extensive as the entire United States, various genetic factors of soil formation should predominate in certain locations. Marbut *et al.*[1] have divided the United States into thirteen areas, seven provinces, and six regions, mainly on the basis of soil genesis. (See Chart 8, pp. 344-5.)

Each of these areas has a characteristic formation. That of the provinces is well defined; that of the regions less so. In the following discussion of the various areas, a description of the location, derivation, topographic and climatic features, and crop adaptation is given.[2]

The Provinces

70. Soils of the Piedmont Plateau Province.—The Piedmont Plateau is a rolling to hilly section extending eastward from the foot of the Appalachian Mountains. The northern end lies in northeastern New Jersey. The area extends in a belt, 20 to 50 miles in width, southwestward and through central Virgina, where it widens and extends through North Carolina, western South

[1] Marbut, C. F., Bennett, H. H., and Lapham, J. E., "Soils of the United States," *U. S. Dept. of Agric. Bur. of Soils Bul. 96.* 1913.

[2] Due to the fact that extensive changes in soil survey methods and soil classification have been made since the publication of *Bulletin 96*, no attempt will be made to discuss the various types of soil in the different areas. The soil types occurring in a localized area are of greater importance to the investigator of that area than those in other localities. The student is urged therefore to consult the soil survey reports of his particular area for detailed information.

For more extended practical application of soils to certain cultural practice, the reader is referred to the following:

Forestry: Bowman, I., *Forest Physiography.* John Wiley and Sons, Inc. New York, 1914. 759 pp.

Horticulture: Gardner, V. R., Bradford, F. C., and Hooker, H. D., *Fundamentals of Fruit Production.* McGraw-Hill Book Co. New York, 1922. 686 pp.

General: Bennet, H. H., *Soils and Agriculture of the Southern States.* The Macmillan Co. New York, 1921. pp. 399. Whitney, M., *Soils and Civilization.* D. Van Nostrand Co. New York, 1925. 278 pp.

Lyon, T. L., and Buckman, H. O., *The Nature and Properties of Soils.* The Macmillan Co. New York, 1926.

Carolina, and northern Georgia and to central Alabama. The province has a length of 900 miles and an estimated area of 47,214,000 acres.

I. Derivation.—The soils are residual, having been derived directly by disintegration and more or less complete decomposition of the parent rock, which lies from a few inches to over fifty feet below the surface. There has been little mixing of the soil material except as it has eroded from the higher levels. The surface soils are of the heavier types; deep sands are uncommon. The subsoils usually consist of a heavy brittle clay.

The parent rock consists of igneous or highly metamorphosed material such as granite, gneiss, and to a small extent sandstones and shales. The northern portion is derived from metamorphosed rocks such as gneiss and chlorite schist, while the southern portion, below the middle of Virginia, is derived from granite with some gneiss.

II. Topography.—The surface is generally rolling and varies from about 300 to 1000 feet above sea-level. The valley slopes are usually smooth and rounded rather than rough and angular. A large portion of the area is tillable from the stream bottoms to the tops of the hills.

III. Climatic Features.—The soils have developed under a mean annual temperature ranging from 50° F. at the northern extremity to 65° F. at the southern extremity. The average rainfall of the area is about 45 inches. Due to the great length of the province and the difference in altitude, there is a wide variation in the temperature. The average mean temperature is 66° F. at the southern end and 52° F. at the northern end.

IV. Crop Adaptation.—The area is not adapted to any special crop; corn, small grains, potatoes, and tobacco will succeed throughout the province. Cotton is restricted to the southern portion. Apples will do well throughout the entire area and certain portions are well adapted to the growing of certain varieties. Certain areas are well adapted to the growing of truck and orchard crops, while others are adapted for grazing and dairying.

71. Soils of the Appalachian Mountain and Plateau Province.—The soil area designated as the Appalachian Mountain and Plateau Province is divided into three main areas. The most eastern area, known as the Blue Ridge belt, extends in a narrow strip from New Jersey to Alabama. The larger portion, known

as the Allegheny and Cumberland Plateau, occupies the greater part of central and western Pennsylvania, the southeastern portion of Ohio, the greater part of West Virginia, and the eastern portion of Kentucky and Tennessee. The third great area, known as the Ozark Region, lies in northern and central Arkansas and eastern Oklahoma. In addition to these areas, there are several others much smaller in size. The area of the province is estimated at 84,837,000 acres.

I. Derivation.—The eastern portion of the province consists merely of an uplift of the western edge of the Piedmont Plateau and is derived of the same material as that province. The portion to the west of this uplift at one time consisted of an ocean floor upon which limestone beds were formed, the coarser materials consolidated into sandstones, the finer into shales, and the whole elevated by earth movements into a succession of ridges and high plateaus. The detached portions in western Arkansas are derived mainly from sandstones and shales, with a few isolated areas from crystalline rocks.

While the soils are residual, they are mainly derived from rocks that were themselves formed of such materials that had been previously transported by moving waters and afterward consolidated. Where the surface is smooth, the soils lie directly over the rocks from which they have been derived. On the slopes, there has been considerable movement, due to creep and water action, to the lower levels. There are large areas over which rocks have been deposited often so thickly as to prevent cultivation.

II. Topography.—The surface is characterized by being quite hilly; steep slopes predominate. In many places the area is unsuited for cultivation except in those valleys that are free of rock débris.

III. Climatic Features.—While the rainfall is greater in the eastern portion than in the western, it is sufficient in most cases to support the growth of agricultural crops. The elevation, however, is such as to cause a short growing period in the higher altitudes and a more favorable condition in the valleys. There is also a variation due to the differences in latitude.

IV. Crop Adaptation.—The general crop adaptation is about the same as in the Piedmont Plateau except that such fruits as peaches, apples, and grapes give a better return in certain areas

and along certain slopes. Large areas are suited only for forestry and grazing.

72. The Limestone Valleys and Uplands Province.—The Limestone Valleys and Uplands Province includes two divisions, the limestone valleys and the limestone uplands. The valleys are most extensively developed within the Appalachian Mountains, extending from New Jersey to Alabama in a narrow strip and including an area in central Tennessee and the blue grass region of Kentucky. The limestone uplands include a large area extending from Alabama through Tennessee and Kentucky almost to the Ohio River. An area known as the Ozark Dome lies in southern Missouri, northern Arkansas, Oklahoma, and southern Kansas. The province has an area of approximately 67.870,000 acres.

I. Derivation.—The soils are residual, having been derived from calcareous rock that has been mixed with an amount of non-calcareous material, usually clay, silt, and sand. The rock was water-formed, the non-calcareous material having been deposited on the floor of the sea, and by more or less complete crystallization of the basic carbonates has been consolidated into beds of hard limestone rocks. These rocks are highly resistant to physical disintegration, as temperature changes, etc., but are readily attacked by the chemical forces of weathering, for instance, by carbonic acid in solution.

II. Topography.—The surface of the area is gently rolling and in the main is admirably adapted to tillage operations. The uplands are more of the character of an even upland plateau. The valleys have an elevation of 500 to 1000 feet in the northern and southern parts with a greater elevation in Tennessee. The uplands have an elevation of 1000 to 1700 feet. The greatest elevation occurs in the Ozark region. Drainage is excellent throughout the area. In some cases the streams have cut secondary valleys from a few feet to 250 feet or more below the valley floor.

III. Climatic Features.—The climatic conditions vary with the altitude and the latitude as in the Piedmont Plateau Province. Usually there is not sufficient difference in elevation to bring about any marked alteration in the type of agriculture.

IV. Crop Adaptation.—As the soils of this region are inherently productive, and as the greater part of the area is suitable

for agriculture, the agricultural soils form highly valuable farming lands. All the general crops, such as grains, legumes, and grasses, grow abundantly, and the greater portion of the area is suitable for tobacco culture. The raising of fruits in these areas is profitable where a suitable air drainage can be secured.

73. The Glacial and Loessal Province.—The Glacial and Loessal Province occupies the northern portion of the United States from Maine to Montana. The southern boundary follows roughly the Missouri and Ohio rivers from Montana to Ohio, with a narrow strip paralleling the Mississippi River, 10 to 40 miles in width, extending from the Ohio River to Louisiana. Small patches are found west of the Mississippi and the Missouri rivers. In Ohio, the southern boundary of the area leaves the river just east of Cincinnati, and extends in a northeastern direction through the northwestern corner of Pennsylvania to the New York line where it turns southeastward to New York City. The area of the province is estimated at 385,000,000 acres.

I. Derivation.—The soils are transported, having been formed by the grinding action of ice or by the carrying forces of wind and water. The ice or glacial-formed soils are found north and east of a line running from Cincinnati to LaCrosse, Wisconsin, thence south to Iowa City, Iowa, and westward to the southeastern corner of South Dakota. South of that line, the soils are mostly wind formed, loessal. The line of demarcation is not clearly defined, due to some material, evidently loessal, that forms a mantle along the edge. The glacial soils may be unassorted (heterogeneous mixtures of all sizes running from clays to boulders) or assorted (the finer particles being deposited in one area and the coarser in another). The glacial soils are usually thin in the higher elevations but quite deep in the lower.

II. Topography.—The surface of the area east of the Ohio-Pennsylvania line is hilly and in general resembles that of the previous provinces. West of this line the topography is in general gently undulating to rolling, smooth or almost flat, except along the larger streams and in the northern part. Drainage is usually good east of the Ohio-Pennsylvania line. West of this line, especially in the flat areas, drainage may be one of the main agricultural problems. In the northern and sandier portions of this area, drainage may be so efficient as to cause crop losses by drought.

III. Climatic Features.—The area varies widely in climatic features. It has a range of 46° in longitude and 12° in latitude. This feature connected with variations in precipitation, temperature, and length of growing season has a marked influence upon the character of the crops grown. The precipitation varies from 45 inches in New England to 15 inches or less in Montana. During the winter, the temperature in northern New England and New York drops to such a point that only the hardiest fruit trees can withstand it, while in Montana and North Dakota it drops approximately 20° lower. The length of the growing season varies from 90 days in Montana to over 200 along the Ohio River.

IV. Crop Adaptation.—The area west of the Ohio-Pennsylvania line is admirably adapted for the production of all farm crops capable of growing under the particular climatic conditions; in fact it may be looked upon as the best grain area of the United States. East of this line the agricultural situation may be said to be at a standstill. In some areas, particularly those that are rough or adjacent to the large cities, interest in agriculture has declined. Certain areas are adapted to horticultural crops, others to dairying or general farming, and still smaller areas may be especially adapted for some special crop as onion, celery, tobacco, grapes, etc.

74. The Glacial Lake and River Terrace Province.—The Glacial Lake and River Terrace Province does not occur as a single large area but as a great number of small areas surrounding the Great Lakes and in northwestern Minnesota, eastern North Dakota, and northeastern South Dakota. These deposits were formed in the basins of more or less temporary lakes, created during the glacial period, or were left by the streams that flowed from the ice of these periods.

I. Derivation.—The soils are transported, being reworked glacial débris, and show very little of their original source. They are of very recent age and are the most recent deposits of any size in the country. A considerable portion of the soils are clays.

II. Topography.—The surface is in general flat or nearly so, consisting of smooth to gently undulating plains. As a rule, there is sufficient slope to provide good natural drainage or to render artificial drainage effective. Some of these soils, however, may be so sandy as to be leachy and droughty.

III. Climatic Features.—The climatic features are essentially the same as those of the northern portion of the Glacial and Loessal Province except as they are tempered by the close proximity of the Great Lakes, thus lengthening the growing season.

IV. Crop Adaptation.—The areas surrounding the Great Lakes, whenever drainage is effected, is adapted to fruit and truck crops, sugar beets, general farming, and dairying. The region in Minnesota and the eastern Dakotas is especially adapted to spring wheat, oats, barley, flax, and grass.

75. The Atlantic and Gulf Coastal Plains Province.—The Atlantic and Gulf Coastal Plains Province includes roughly the seaward margin of Long Island, N. Y., the southern two-thirds of New Jersey, nearly all of Delaware, the eastern and southern two-thirds of Maryland, the eastern third of Virginia and North Carolina, the eastern half of South Carolina, the southern half of Georgia, all of Florida, and the southern and western two-thirds of Alabama, the eastern half of Mississippi, and a narrow strip in western Tennessee. There is a broad gap in the Gulf plains along the Mississippi River. West of the Mississippi the area includes the southern third of Arkansas, a narrow strip of southeastern Oklahoma, the western two-thirds of Louisiana, and the eastern and southern two-fifths of Texas. The area of the province is estimated at 218,000,000 acres.

I. Derivation.—The province is a vast outwash plain built of the material carried down by the regional drainage from the older mainlands to the rear (the Piedmont Plateau, the Appalachian Mountains and Plateaus, the Limestone Valleys and Uplands, the Glacial and Loessal Provinces, and the Residual Prairie Regions) and deposited in former coastal waters through a long period of time and under various conditions of sedimentation. This has resulted in a soil mixture varying from the coarsest gravel and sand to the finest silt and clay. The solvent action of the water has left only the harder particles, chiefly quartz, as the dominant constituent of these soils.

II. Topography.—The surface in general has the appearance of a dead-level plain, varied by slight hillocks and ridges along the coast, with more pronounced variations in the interior. The slope is approximately two feet to the mile, consequently the elevation varies from slightly above sea-level to 500 or 600 feet along the inner margin.

III. Climatic Features.—The climate ranges from the subtropical immediately along the Gulf coast to the moderately temperate in the latitude of New York. Due to the close proximity to the ocean and gulf, the area is favored with a more equable climate than is found in other parts of the eastern half of the United States. The rainfall over the major portion of the area varies from 40 to 60 or more inches, the greater portion falling during the growing season. The growing season varies from 260 days in Texas and Florida to 180 in central and northern New Jersey.

IV. Crop Adaptation.—These soils may be said to be the truck soils of the United States because of the fact that they have a monopoly of the markets of a large part of the country for fresh fruits and vegetables for over six months in the year. The range in latitude, over 1000 miles, the favorable climatic condition, the rather slow advance of spring northward, and the difference in time of maturity of the different crops enable this area to send a constant supply of highly perishable products to the northern markets. These products are first vegetables and berries, followed by fruits of various kinds. There is a progressive movement of the source of supply, of these vegetables and fruits, due both to the advance of the season and to the influence of the texture of the soil. This movement may be grouped into six periods corresponding roughly with the first six months of the year, as shown in Table No. 2.

TABLE 2

EFFECT OF SOIL TEXTURE ON THE MARKET PERIOD OF VEGETABLES AND FRUITS FROM THE ATLANTIC AND GULF COASTAL PLAINS PROVINCE

LOCALITY	First Period January	Second Period February	Third Period March	Fourth Period April	Fifth Period May	Sixth Period June
Florida ..... Georgia	Sand	Fine sand	Sandy loam	Fine sandy loam	Loam	Silt loam
South Carolina	.....	Sand	Fine sand	Sandy loam	Fine sandy loam	Loam
North Carolina	.....	....	Sand	Fine sand	Sandy loam	Fine sandy loam
Virginia ...	.....	....	....	Sand	Fine sand	Sandy loam
Maryland . Delaware ..	.....	....	....	....	Sand	Fine sand
New Jersey Long Island	.....	....	....	....	....	Sand

In addition to fruits and vegetables, these soils are fairly well adapted to the growing of the main agricultural crops. Rice and sugar cane are confined to the Gulf States, cotton to the area south of Norfolk, Virginia; corn, cowpeas, and vegetables are grown from Texas to New York.

76. River Flood Plains Province.—The soils of this province occupy the first bottoms and adjoining terraces of streams in all parts of the United States. The original description of this area covered only that portion east of the Great Plains region. Some areas of flood plains soil cover the bottoms and terraces of valleys which have been abandoned by their main streams. These soils occur in continuous and interrupted steps along the banks of streams. Their outer boundary ordinarily is marked by a steep slope rising to the uplands. They vary in width from a narrow strip a few feet wide to broad bottoms several miles wide. The broadest strip is that along the Mississippi River near where the Arkansas joins it, where the bottoms range from 75 to 100 miles wide. This province is best developed along the larger streams of the coastal plains where the gradient is slight and the material offers little resistance to the stream. In the Appalachian Mountains and Plateau, the tendency of the streams has been to cut downward rather than outward. This is due both to the higher level and to the harder material through which the streams flow.

I. Derivation.—The stream bottoms and terraces are made up of alluvial material consisting of deposits washed from slopes and uplands and deposited down stream by overflow waters. The material may be very simple in character or it may be an extremely heterogeneous deposit derived from several drainage basins, including soils widely variant in texture and character. The distance transported has also had an influence in determining the shape and size of the particles. There has been considerable assorting of the stream-carried material by variation of the current and some wearing down of the coarser particles, but the streams have done much less of this work than have the waters of the ocean. The gravel and coarser sands are largely left along the upper courses, the fine and medium sands in the natural levees along the banks, while the finer particles enter the sea to be thoroughly assorted.

There has been relatively little opportunity for changes in the first bottom deposits by weathering on account of poor drainage

and the addition of fresh deposits. On the other hand, a great part of the terrace material is well drained and has been considerably altered by weathering. Some of the better drained portions of the terraces comprise material which closely resembles the still older upland material. This is to be expected from identical conditions of weathering, often of material derived from the same original source.

II. Topography.—The soils of this province include two topographical divisions—the first bottoms or present flood plains, and the terraces or old flood plains. The bottoms are usually level or essentially so, while the terraces include old flood plains which now stand largely above the influence of overflow water. In their height above the first bottoms, the terraces vary from a few feet to several hundred feet. There is often a series of distinct terraces arranged one above another in step-like succession. The surface features of the terraces vary from flat to rolling. Those nearest the streams ordinarily have smooth flat surfaces, while long-continued erosion may have affected the higher ones.

III. Climatic Features.—Inasmuch as the soils of the River Flood Plains Province are developed over a very large area, it is evident that the climatic variation is wide, ranging from subtropical in the south to the long winters of the north, and from semi-aridity in the west (decided variation in the far west) to humidity along the Atlantic shores. In general, the climate may be said to be that of the area in which the particular soil area occurs. Usually the bottom soils, being poorly drained, do not warm up as early in the spring, and the net result is that the growing season is shorter than that of adjacent uplands.

IV. Crop Adaptation.—The soils of this province comprise a vast area of extremely fertile land. To a very large extent they represent the most fertile lands known. The soils possess great potentialities and only require drainage and protection from overflow to become producers of a variety of crops. Corn does well on most of these soils. Truck is an important crop in the southern part, but in the northern portion of the country these soils are not so well adapted to such crops.

The Regions

The regions are broad geographic areas throughout which uniformity in climatic conditions, topographic relief, or other domi-

nant factors tend to give a certain degree of similarity to the various soils. Each region may contain several areas possessing characteristics similar to those upon which the province has been founded. It is quite probable that, as the soil survey progresses, the extensive areas of the regions will be further divided.

77. The Great Plains Region.—The Great Plains Region is bounded on the north and east by the Glacial and Loessal Province, following generally the course of the Missouri River; further south by the Ozark uplift and the Gulf Coastal Plain. It extends to the Rio Grande on the south, and is bounded on the west by the Rocky Mountains and the Pecos valley.

The region thus extends from Mexico almost to Canada, and has a maximum width of about 600 miles. It covers all or a part of twelve large western states.

I. Derivation.—The Great Plains Region consists of the non-glaciated part of the western prairies and plains. The varying conditions of this area and the methods of soil formation have given rise to several distinct physiographic and soil provinces within the region. These are (1) residual material formed from the weathering in place of sedimentary rocks including sandstones, shales, and limestone; (2) glacial material which is not at all extensive; (3) lake-laid material, which has been derived through the erosion of fine soil material and its deposition in shallow waters or depression of ponded drainage courses; (4) wind-laid material, which is of doubtful geologic origin but very similar to the soils of the residual province; (5) alluvial fan and valley-filling material, which has been derived from the great areas of Tertiary deposits mainly consisting of fragments of quartz and feldspar; and (6) the river flood plain material which occurs as alluvial deposits along the streams of the region. The residual, wind-laid, and alluvial fan provinces are the most extensively surveyed.

II. Topography.—The region reaches a height of 6000 feet at the middle of the western boundary, sloping to an elevation of some 2000 feet along the northern part and 1000 feet along the southern part of the eastern boundary. Such an elevation has aided erosion and in many places the surface is level or gently sloping.

III. Climatic Features.—This area covers a wide range of climatic conditions, from warm and long summers in the south,

to short growing seasons and cold winters in the north. The western part is also arid and requires irrigation for the production of most crops. The eastern part receives from twenty to thirty inches of rainfall, and is therefore better adapted to general agricultural operations.

IV. Crop Adaptation.—The more humid portions are extensively utilized for the production of corn, wheat, flax, cotton, and other staples. In the greater part of the semi-arid area irrigation is necessary, but where the soil is properly irrigated large areas of the valley and plains soils are valuable for the production of alfalfa, grains, and special crops, such as sugar beets, melons, etc. Extensive areas of the more arid regions are also utilized for grazing.

78. Rocky Mountain and Plateau Region.—This area embraces western Montana, northern and central Idaho, northeastern Washington, western Wyoming and Colorado, more than half of Utah and Arizona, and about one-half of New Mexico, in addition to isolated areas in eastern Wyoming, South Dakota, and Texas. The region falls into two distinct and characteristic physiographic provinces, consisting of the Cordilleran, the Mountain portion, and the Plateau districts of the central and southwestern sections.

I. Derivation.—A variety of rocks is represented, the most of which have been crushed, folded, and faulted. These include granite and other quartz-bearing as well as quartz-free intrusive and effusive rocks, limestones, and other rocks of sedimentary origin. Extensive areas of the higher and more northern ranges of the region have been slightly glaciated, a few remnants of which remain.

The plateau portion is characterized by gently tilted or horizontal rocks, sandstone and shales predominating. This area consists of several geological areas or soil provinces. The most important are the residual, which are soils derived from sedimentary deposits; alluvial fan and valley soils which occupy areas of gentle or rather pronounced slope; lake-laid material, which consists of soil formed from sedimentary deposits and extinct lakes; and river flood material.

II. Topography.—The topography of this area is mountainous, particularly in the northern part. The range in elevation is from 3000 feet to more than 14,000 feet, with much of the area lying

at more than 8000 feet elevation. The plateau portion ranges from 5000 to 7000 feet in altitude.

III. Climatic Features.—The lower and more southern regions are of arid and semi-arid character and but sparsely timbered, while the central and more northern or more elevated areas are subject to heavy precipitation occurring largely as snowfall, and are heavily forested. Springs and perennial streams are abundant over much of the mountain region and the more elevated and more northern parts are sufficiently well supplied with moisture to produce crops without irrigation. As is to be expected at such elevations, the winters are long and severe, resulting in a short growing season.

IV. Crop Adaptation.—This area is inaccessible and its distance from markets, the severity of the climate, and the altitude have hindered its development as an agricultural region. Much of the land is suitable only for grazing. The great expense of irrigating, even where it is possible to do so, has also hindered the development of this country from an agricultural standpoint. The principal crops grown are grain, hay, and along the river flood plains other crops for local consumption.

79. Northwestern Inter-mountain Region.—This region includes the area lying between the Rocky Mountain Region on the north and east, the Pacific Coast Region on the west, and the Great Basin Region on the south. Considerable parts of Washington, Oregon, Idaho, Nevada, Utah, and California are included within its limits.

I. Derivation.—The rocks of this region are predominantly effusive and mainly of basic or basaltic character. In the Plains districts they are made up of sheets which lie more or less horizontally, and have been built up by successive flows of highly fluid rock, probably emanating from fissures or vents now obliterated. Small areas of sedimentary, metamorphic, and quartz-bearing granitic rocks occur in certain sections.

The region falls into three topographic subdivisions which may be designated as the Plateau Plains, the Central Upland and Mountains, and the Klamath-Lassen Peak Districts. The soils belong to several provinces, being residual, glacial, loessal, and river flood plains material.

II. Topography.—The Plateau Plains have an altitude of from 100 to 6000 feet, and have a flat to undulating topography.

Streams are of infrequent occurrence, flowing through deep flat valleys with steep rocky walls. In places, outcrops of effusive lava sheets are present.

The Central Upland portion lies at an elevation of from 5000 to 9000 feet, and in many cases is rocky and barren.

The Klamath-Lassen Peak district consists of desert plains of filled valleys, broken by rocky ridges, volcanic cones and plains, elevated basaltic plateaus and occasional broad shallow lake basins.

III. Climatic Features.—The climate of the Plains region is marked by a wet and dry season with a limited rainfall There is a wide range of seasonal temperatures, with hot summers and cold winters. Clear days are numerous, the humidity is low, and at certain seasons the winds are excessive. The more elevated upland and mountain districts have a greater precipitation, and are better adapted to grazing. In frequent cases, they are heavily forested.

IV. Crop Adaptation.—This area is better adapted to grazing and extensive farming rather than to intensive. Dry farming is practiced in certain areas; and where irrigation is not prohibitively expensive general field crops adapted to the climate, such as grains, hay, etc., are planted.

80. Great Basin Region.—The Great Basin region occupies that area of the western United States which is drained to the interior. It embraces practically all of Nevada and parts of Utah, Idaho, Oregon, and California. With the exception of one small lake, no drainage water from this area finds its way to the sea, and with only minor exceptions no drainage from other regions enters into the Great Basin.

I. Derivation.—The region is characterized by the numerous isolated ridges and mountain ranges running in a general north and south direction. The exposed rocks of the ranges and hills are mainly of recent effusive and intrusive volcanic character, basalts, rhyolites, diorites and andersites predominating, with some granitic rocks. Quartzites with limestones, conglomerates, and other older sedimentary rocks are of an extensive occurrence. Some of the more elevated ridges evidence former glaciation which, however, has not influenced the character of the soil.

In certain parts of the region, broad basin-like depressions formerly occupied by extensive lakes are found. The larger of

the extinct lakes are Bonneville in Utah, now represented by the Great Salt Lake; and Lahontan in Nevada, now represented by Carson and other lakes. The soils are residual, volcanic, lake-laid, and river flood plains material.

II. Topography.—The topography of this region is in general mountainous. Long narrow ridges and ranges of monoclinal structure occur. The bases of the desert mountain ranges are deeply buried beneath accumulations of detrital material. The crests of the mountain ridges are usually rugged and barren or occasionally scantily timbered; associated with the main ranges are occasional mesas and low-lying hills. The elevation ranges from below sea level in Death Valley, California, to more than 10,000 feet.

III. Climatic Features.—The region includes the most extensive areas within the United States which typify or approach true desert conditions. Throughout the greater part of the area, the rainfall is decidedly limited.

IV. Crop Adaptation.—The greater part of this area can be successfully farmed only when irrigated. Large areas are adapted only to grazing, but where irrigation is possible, grain and hay crops may be profitably produced. With the development of transportation facilities, certain areas now devoted mainly to general farming should become capable of very efficient and economic utilization for sugar beets, fruits, and other intensively cultivated products.

81. Arid Southwest Region.—This region covers the southwestern third of Arizona, a large area in south-central New Mexico, and in northwestern Texas. It also includes a small area in southeastern Nevada and the southeastern extremity of California.

I. Derivation.—From the desert plains of this area rise frequent low rounded hills, occasional flat-topped mesas, and many isolated elongated mountain ridges. Like the ranges of the Great Basin province, the bases of the mountains are partly filled by deposits. The rocks of mountain ranges, where exposed by erosion, consist mainly of Pre-Cambrian gneisses or related crystalline rocks or Tertiary eruptives. Some areas of the older sedimentary and metamorphic rocks occur.

The soil-forming agencies in this region are weathering, wind action, deposition, with subsequent elevation of substances depos-

ited in the sea, inland lakes, and the transportation and deposition of stream-borne material. These agencies have formed coastal plains, river flood plains, lake-laid, loessal, and residual material.

II. Topography.—The region covered by this province consists predominantly of sandy, gravelly, and sloping or flat, treeless, desert plains. Greater elevations of hills, mesas, and ridges occur. The higher elevations are from 5000 to 7000 feet.

III. Climatic Features.—This region has an arid climate with long hot summers, mild winters, low relative humidity, and long unbroken periods of sunshine. Evaporation of moisture is excessive. Frosts are of frequent occurrence in most of the region during the cooler months, although severe freezes are infrequent except in the most elevated districts.

IV. Crop Adaptation.—This region is not generally adapted to farming with irrigation but where it is possible to successfully irrigate, grain, alfalfa, fruits, truck crops, and cotton are extensively grown.

82. Pacific Coast Region.—The Pacific Coast Region includes those portions of California, Oregon, and Washington west of the crest of the Cascade, Sierra Nevada, Sierra Madre, and San Jacinto Mountain ranges.

I. Derivation.—This area is bounded by and has mountain ranges extending throughout its entire length. These mountains are composed largely of highly metamorphic rocks of various kinds. Sedimentary and altered sedimentary rocks occur. There are marine deposits between some of the ridges. The resulting soil material represents the characteristics of practically each of the provinces.

II. Topography.—The topography of this area is characterized by a broad structural valley depression interrupted by mountain ranges and lesser ridges. The southern portion is represented by the interior valley of California. The floor of this structural trough is not greatly elevated above sea level and is of level to undulating or gently rolling character. In places, the mountain ranges reach altitudes of 10,000 to 14,000 feet. The region covered by the Coast ranges includes many stream valleys, some of which are highly developed and of great agricultural importance.

III. Climatic Features.—The climate of this region presents a startling variety of conditions. Along the northwestern coast, there is an annual rainfall of 80 to 100 inches, and in extreme

southern California precipitation in some places is almost negligible. Active glaciers occur along the higher peaks of the Cascade and Sierra Nevada ranges, and are contrasted with the production of semi-tropical fruits of the southern part of the region.

PART II

THE PHYSICAL PROPERTIES AND FUNCTIONS OF SOILS

All things possess certain physical properties and are subjected to the related phenomena of matter and energy. The soil is a complex mixture of more or less solid particles, each of which has its individual physical property that has more or less effect upon the physical properties of the whole. The soil mass, however, does not consist entirely of solids; rather, it consists of matter in three states, namely, the solid, the liquid, and the gaseous. Consequently the function of the soil mass from the physical standpoint depends upon the relationship existing between its three states, subject to the physical properties of those states.

CHAPTER 7

THE PHYSICAL FORMATION OF SOIL

The physical formation of soil is a result of those processes of disintegration and decomposition associated with movement (**20**). The motion may be such that the result is soil formation at varying distances from the rock material from which it is derived. The distance moved may be very slight, slight, or great, according to the force or forces involved.

83. Forces Involved in Soil Formation.—Any force causing movement, directly or indirectly, of the rock mass that may be ultimately disintegrated, may be considered as a factor in soil formation. Thus we may have *very slight movement* due to crustal changes, temperature changes, results of impact, etc.; *slight movements* due to biological action, etc.; or *greater movements* due to the various states of water or to wind action, or to a combination of forces. Of course the degree of movement is only arbitrary, consequently a very slight movement at first for instance on a slope, may, due to gravity, develop rapidly into a much greater movement. The combined physical forces causing soil formation may be combined under the heading of the *physical forces of weathering.*

84. Forces Causing Very Slight Movement.—These forces may be listed as: (1) Crustal changes of the earth's surface, (2) Temperature changes, and (3) Results of impact from particles in rapid motion.

I. The Influence of Crustal Changes.—It is difficult to estimate the influences of changes in the earth's crust upon soil formation. During the Proterozoic geological era (**14,** *II*), the surface began to be pushed up in certain localities, the movement continuing through the Paleozoic (**14,** *III*) and Mesozoic eras (***14,*** *IV*). The extent of this crustal movement from the standpoint of variations from the horizontal can only be conjectured, but there is every reason to believe that some areas have subsided while others have been forced to great heights. These changes were very

slow and, directly, had very little influence upon soil formation. Indirectly, they were of the greatest importance as they placed the soil or the soil-forming materials in a position to be disintegrated at a later period. The various factors concerned in soil formation at the present time, however, are apparently causing a leveling off of the earth's surface. Every time a particle is loosened, it is affected by gravity, consequently if moved seeks to go to the lowest possible level.

II. The Influence of Temperature Changes.—Changes in temperature have a very marked influence upon soil formation due to the fact that most solids expand when heated and contract when cooled. The various constituents of the soil, however, react differently to temperature changes; that is, they differ in their coefficient of expansion. This is especially marked in the case of the mineral particles. For instance, the coefficient of expansion of quartz is 0.000007 to 0.000014; of iron, 0.000012; of glass, 0.0000088, and of lead, 0.000029. Gases also expand when heated and contract when cooled, but in a more or less definite ratio. Water, however, expands when heated and contracts when cooled [1]

TABLE 3

RELATIVE DENSITY AND VOLUME OF WATER [2]

TEMPERATURE °C †	DENSITY	VOLUME
—5	0.99930	1.00070
0	0.99987	1.00013
4	1.00000	1.00000
5	0.99999	1.00001
10	0.99973	1.00027
20	0.99823	1.00177
50	0.98807	1.01207
100	0.95838	1.04343

† Under normal conditions, water freezes at or slightly below 0°C. The density of ice at 0° is 0.9164. Then the volume of ice, secured from a volume of water, is 0.99987 ÷ 0.9164, or an increase in volume of 9.1 per cent. If water is confined, this increase in volume, due to freezing, exerts a tremendous pressure, approximately 150 tons per square foot.

only to about 4° C., when it again expands, consequently ice occupies a greater area than an equivalent amount of water. These different reactions to temperature of the three soil states have a marked effect on soil formation, the solid and liquid states

[1] Water possesses the peculiar property of contracting until the temperature of 4°C. is reached. Above or below this point there is a decrease in density and an increase in volume (see Table 3).

[2] *Handbook of Chemistry and Physics*, 10th ed., p. 438. Chemical Rubber Publishing Company. Cleveland, O., 1925.

being particularly affected, while the effect of the gaseous state is, to a certain extent, unknown.

Under ordinary conditions, rocks are warmed during the day and cooled during the night. The degree of heating depends upon the position of the mass in respect to the sun's rays, the color of the material, and the ability of the mass to absorb and to conduct heat. The degree of cooling depends primarily upon air temperature and rain. If the rock consists of one mineral, for instance, a limestone, the variation in temperature will have little influence in breaking it down, unless it should be a poor conductor, in which case changes of temperature will cause lateral stresses. If, however, the rock is composed of different minerals or of a mineral having a complex chemical constitution, there may be quite a variation in the coefficient of expansion between the particles.[3] This variation causes differential stresses throughout the mass which eventually results, when repeated throughout the years, in a tendency to form minute fissures between adjacent particles, crystals, or masses in the aggregate. This causes either a direct rupture or a condition allowing the entrance of water, dust, plant life, etc., that brings about a gradually increasing rate of surface disintegration or decomposition, due to the combined physical, chemical, and biological actions. When water flows into the tiny crevasses and the temperature drops to the freezing point, the rock mass is still further disintegrated.

III. The Influence of Impact.—Particles may be carried by various agencies (wind and water) and these particles strike other particles or masses of particles. The result of continued impact causes a loosening or grinding of the surface structure of the mass. The action may be illustrated by a sand blast used to clean the surface of buildings.

85. Forces Causing Slight Movement.—The forces causing slight movement are, in reality, a continuation of the previous group, differing, however, in the fact that they are concerned

[3] The surface of a rock will become heated according to the exposure to the direct rays of the sun. The heat will penetrate the rock according to the ability of the minerals to conduct it to the interior. The rate of conduction affects the uniformity of expansion. If the mass does not expand uniformly, lateral stresses may be set up, causing a breaking apart of the aggregates, or in some cases a peeling (exfoliation) of the surface. The action is intensified when the mass is cooled. In this case, the surface contracts while the heated portion below is still expanded. The débris (talus) at the foot of cliffs is mute evidence of this action.

primarily with life. Animals and in some cases plants have a limited influence upon the physical formation of soils in some localities, and a very important influence in other locations. Small animals, squirrels, moles, mice, crustaceans, insects, worms, etc., affect the soil chiefly by burrowing or tunneling (**53, 2**), thus allowing the entrance of the agencies of weathering. The movement of soil material by moles and by earthworms is well known. The action of the smaller animals is not so apparent. The ant is probably the most active of the smaller animals, due to the fact that it brings up masses of soil particles from the lower depths. In the tropics, great mounds are often formed in this manner. In certain parts of Africa, the native population is dependent on these mounds for their sustenance because the other portions of their fields are barren.[4]

86. Biologic Life as Rock-Forming Agencies.—Throughout the ages, water has been an important agency in all physical and chemical soil processes. It has been very active in denuding the soil of its soluble materials and frequently of its smaller particles. The materials carried by the water formed the main source of food supply for the very extensive flora and fauna of both fresh and saline waters. This biological life withdrew or segregated from the waters the various materials and deposited them as more or less insoluble compounds, which, tending to collect in masses, were capable of re-forming as rocks. As an illustration, the formation of the various forms of limestones is possibly the most common. This action is seen in the formation of coral reefs, etc. The living coral first deposits large amounts of calcium carbonate and smaller amounts of other materials about itself as a protective covering. When the coral dies, the dead fragments are broken into sand-like particles by the waves. These particles by solution and redeposition of calcium carbonate are cemented into solid rock. Such rock material may contain the entire

[4] On the barren plateau of Unyamwezi, German East Africa, the natives are largely indebted to the termite *Termes bellicosus* for their crops. The soil has little fertility and the art of fertilization is unknown to the negroes. The large moundlike nests of the termites consist of a rich and fertile loam. The crops are planted on these mounds, which are scattered like oases (dark green and thickly overgrown) in the otherwise semi-barren fields.

The nests are 6 to 10 feet in height and about 25 feet in diameter. The material of the nests is not only suitable for crops but is prized for the making of walls and floors in the native huts. *Literary Digest*, Vol. 88, No. 8, p. 27. Feb. 20, 1926.

skeleton of the original animal. On the other hand, aquatic plants, absorbing carbon dioxide from the water and setting oxygen free, frequently obtain the former at the expense of any calcium bicarbonate in solution, depriving that compound of its second molecule of carbon dioxide and causing the precipitation of calcium carbonate. The formation of incrustations of lime about aquatic plants is attributed to this action. The decomposition of the soft portions of the body of aquatic animals, with the resulting formation of ammonia or any other alkaline carbonate, would, in the case of waters saturated with calcium carbonate, cause a precipitation of the latter.

Lime rocks may be laid down under diverse conditions. Clarke [5] states, "An oceanic ooze may produce a soft flour-like substance such as chalk, or a mixture of carbonate and sand, or one of carbonate and mud and clay. Calcium carbonate transported as silt, may solidify to a very smooth fine-grained rock, while shells and corals yield a coarse structure full of angular fragments and visible organic remains. Buried under other sediments any of these rocks may be still further modified, the fossils becoming more or less obliterated, until, in the extreme case of metamorphism, a crystalline limestone is formed." It is supposed that the extensive phosphate deposits have been formed in much the same manner, but by different chemical processes. The iron bacteria [6] are credited with providing important material for the cementation and binding of small particles or even gravel and rock masses into large aggregates or formations.

87. Biologic Life as Soil-Forming Agencies.—We know little regarding the soft-bodied biological life (bacteria, fungi, higher plants, etc.) that evidently existed in various degrees of abundance during prehistoric times. The introduction of marine life during the Paleozoic area (**14**, *III*) implies the existence of vegetable life to supply energy-containing food. It must be remembered that the greater portion of the present exposed earth's surface was at one time the bottom of a sea. The marine oozes formed during these periods and consisting of sediments [7] of

[5] Clarke, F. W., "The Data of Geochemistry." *U. S. Geol. Sur. Bul.* **770.** 1924. 841 pp.

[6] Harder, E. C., "Iron-Depositing Bacteria and Their Geologic Relations," *U. S. Geol. Sur. Prof. Paper 113.* 1919. Swinnerton, O. C., "Iron Bacteria," *Science*, n. s., *63*, p. 74. 1926. Van Hise, C. R., "A Treatise on Metamorphism," *Monograph U. S. Geol. Sur. 47.* 1904.

[7] See discussion, "Oceanic Sediments," by Clarke, *Bul.* 770, pp. 133-140.

various kinds (gravels, sands, silts, clays, etc.) intermingled with the shells, tests, plates, or other forms of hard coverings of skeletons of marine animals, possibly form the greater portion of our present inland soils. The protective coverings were in some cases calcareous and gave rise to the lime formations discussed above. In other cases, they were composed of non-calcareous materials. The extensive areas of shallow water and a favorable climate provided conditions for the extensive development of all forms of marine life. The echinoderns, especially the crinoids, developed in such abundance during the Paleozoic era that, in some localities, they formed veritable flower beds of "stone lilies." The remains of many of these forms, containing large amounts of both organic and inorganic compounds, have possibly gone far in initiating the important life-giving properties of our present soils.[8] On the other hand, the remains of more recent plants and animals have undoubtedly been a factor in contributing to a continuation and increase of this life-giving property. At the present time, all forms of biological life from the highest to the lowest, both directly and indirectly, by physical and by chemical action influence the formation of soils.

Plants, when alive, have more of a chemical than a physical action in soil formation. There is, however, a certain tendency on the part of the growing root to force the soil mass aside. When the plant dies, the roots decay and the space occupied by the decomposed tissues may act as conduits for the entrance of weathering agencies or the movement of materials from higher to lower levels.

88. Forces Causing Great Movement.—The physical forces associated with great soil movements may be listed as steam, water, ice, wind, and gases, assisted by temperature changes and gravity. As these forces are overlapping in their action, they will be discussed under the heading of volcanoes, water, glaciers, and wind.

I. Volcanoes.—Volcanoes were at one time very active agents in soil formation but are comparatively inactive at present. During the periods of mountain formation and great crustal movements of the earth's surface, great volcanoes were formed for

[8] For analyses of the various forms of marine shell animals, see Clarke, F. W., "The Inorganic Constituents of Marine Invertebrates," *U. S. Geol. Sur. Prof. Paper 124*. 1922.

the release of accumulated gases. These gases were primarily steam, supposed to have been generated by seepage waters striking the hot layers below. The gases were often expelled under great pressures and were accompanied by masses of ash and molten material.[9] Some of the material flowed out as lava and formed rocks, some was forcibly expelled to great heights, and, striking the cooler air above, broke up into small fragments and fell to the earth as ash. It is quite possible that the first soil material was formed in this manner.

II. The Action of Water—At the present time water is possibly the most extensive physical and chemical agency in the formation of soils. When rains fall on the surface, they exert a mechanical effect due to the force of impact. A part of the water may penetrate below the surface, the balance seeking the lowest level naturally runs off. While running from the point of impact to the place of rest, the water exerts further effects on soil formation by sorting, moving, and reworking any material that may be in its path. The water itself acts primarily as a chemical agent in soil formation; but, due to its ability to carry particles of varying size, it becomes a very active physical agent also. Still, water exerts very little physical effect on soil disintegration. It may cause certain chemical changes (hydration), during which crystal formation may take place, thus forcing apart or cementing the rock particles. Moving water, however, has the ability to move soil particles or larger masses and for various distances may carry them in suspension. By carrying particles in suspension, moving water is armed with tools to do further work of disintegration. The ability of water to transport material varies with the speed at which it moves.

III. The Physical Laws of Moving Water.—It is difficult to define water movements accurately. Mosier and Gustafson[10] state: "The work of moving water varies as the square of the velocity. If the velocity is doubled, the work that the stream is capable of doing will be increased four times, since, by doubling the velocity, twice the number of particles will strike an object

[9] The eruption of Mt. Katmai, Alaska, June, 1912, blew off the entire mountain top. It is estimated (*National Geographic*, *33*, 1918) that a mass equivalent to a five-mile cube (11 billion cubic yards) was thrown into the air. For other references, see *National Geographic*, February, 1913, January, 1917, and February, 1918.

[10] Mosier, J. G., and Gustafson, A. F., *Soil Physics and Management*, p. 16. J. B. Lippincott. Philadelphia, Pa. 1917 442 pp.

with double the force." Clear moving water then would have little influence as a physical agent. It would not become an agent until it carried particles of solid material. The ability of moving water to carry this material depends upon the speed with which it is moving. On the other hand, Merrill [11] shows that the capacity of transport by moving water increases as the sixth power of the velocity. In other words, by doubling the velocity, the motor power is increased sixty-four times. He gives the motor power of streams by varying velocities as follows:

STREAMS MOVING

Miles per hour	*Will do the following work:*
0.170	Just move fine clay.
0.240	Lift fine sand.
0.4545	Lift sand as coarse as linseed.
0.6819	Sweep along fine gravel.
1.3638	Roll along round pebbles one inch in diameter.
2.045	Roll along angular stones the size of an egg.

Gilbert,[12] however, claims that the flow of a stream is a complex process involving interactions which have thus far baffled mechanical analysis. He shows that, due to the finer débris being borne in suspension, the coarser being swept along the channel bed with a leaping sliding motion, complications are introduced by variations in width, velocity, slope, depth, discharge, size of particles, character of channel, etc., making impossible the derivation of any general mathematical formula.

IV. The Action of Waves.—The results of wave action are in evidence on all shore lines, so much so that the shore line of ancient seas may be readily traced. As the earth's surface was probably covered many times by prehistoric seas influencing it, with the characteristic action of water, this factor in soil formation becomes of interest.

V. The Process of Denudation.—Erosion is continuous in some areas, intermittent in other areas. Moving water will not only disintegrate rock material but will move (denude) the results of this action to other areas. Just how extensive this action is can

[11] Merrill, G. P., *A Treatise on Rocks, Rock Weathering, and Soils*, p. 288. The Macmillan Company. New York, 1897. 411 pp.

[12] Gilbert, G. K., "The Transportation of Débris by Running Water," *U. S. Geol. Sur. Prof. Paper 86*, pp. 1-263. 1914.

only be conjectured. Hilgard [13] states that the Mississippi River annually carries to the Gulf of Mexico enough soil material to fill one square mile of surface to a depth of 268 feet. In other words, the work of this one stream annually denudes (lowers) the surface of 268 square miles one foot.

Duley and Miller [14] have compiled data from various sources giving the drainage and erosion of several of the important rivers of the world. (See Table 4.)

TABLE 4

DRAINAGE AND EROSION BY SOME LARGE RIVERS

River	Drainage Area Sq. Miles	Mean Annual Discharge Second-Feet	Sediment			
			Total Annual Tons	Ratio Wt. Soil to Wt. Water	Surface Inches Eroded Annually	Years to Erode Top 7 Inches
Potomac ..	11,043	20.160	5,557,250	3,575	0.00433	1,616
Mississippi .	1,214,000	610,000	406,250,000	1,500	0.00288	2,430
Rio Grande.	30,000	1,700	3,830,000	291	0.00110	6,363
Uruguay ...	150,000	150,000	14,782,500	10,000	0 00085	8,235
Rhone	34,800	65,850	36,000,000	1,775	0 01071	653
Po	27,100	62,200	67,000,000	900	0.02612	268
Danube	320,300	315,200	108,000,000	2,880	0 00354	1,977
Nile	1,100,000	113,000	54,000,000	2,050	0 00042	16,666
Irrawaddy ..	125,000	475,000	291,430,000	1,610	0.02005	349

VI. The Results of Erosion.—Practically every slope shows signs of the bodily movement of soil or soil particles due to either water or wind action. In the mountainous or hilly portions of the United States, many striking examples may be found. In fact, the national parks of the West are monuments to the artistic ability of Nature in carving scenic wonders. In the more level areas the action may not be so apparent, due to the fact that the surface portions only are moved. The results, however, are noticed in dust storms, drifted soils, muddy streams, etc.

VII. The Process of Deposition.—If it is true that moving water denudes areas, it is also true that motionless water builds up the soil level in other areas. Thus streams cut down the surface in elevated areas, transport the material to more level areas, and build up flood plains, terraces, etc., in the area of retarded

[13] Hilgard, E. W., *Soils, Their Formation, Properties, Composition and Relation to Climate and Plant Growth*, p. 7. The Macmillan Company. New York, 1907. 593 pp.

[14] Duley, F. L., and Miller, M. F., "Erosion and Surface Runoff under Different Soil Conditions," *Mo. Agric. Expt. Sta. Resch. Bul. 63.* 1923.

flow. The building up of deltas at the mouth of streams and the action of soil formation due to the evaporation of water in closed lakes is partially due to this effect, and in the case of streams flowing into waters of a higher salt concentration, to a chemical precipitation.

VIII. The Action of Ice.—At the present time ice is of little importance in soil formation. It must be remembered, however, that most of the soil in the northern part of the United States was formed by this agent during the Cenozoic era.

IX. The Action of Wind.—Wind action, like water action, is a well-known but intangible factor in soil formation. Moving air currents may and do pick up soil particles, waft them to great heights, carry them great distances, throw them against any immovable masses in their paths with varying force, or roll the larger particles along the surface and deposit them when the movement has been retarded. In this action the moving particles grind and are in turn ground by the immovable masses. The work performed will depend entirely upon the velocity of the wind. The greater the velocity, the greater the mass of particles and the larger the size of the particle carried. In many of the western states, plowing during a dry time will result in a bodily removal of the surface soil, often exposing the gravel below. Such places are called "blowouts." At present, the action of wind is best shown by a study of the movement of sand dunes.

Accurate information on the relative rate of wear or abrasion by wind or water action is lacking. Mackie [15] concludes that, from the standpoint of wear, wind is nearly twenty-nine times as efficient in the rounding of sand grains as is water. Anderson,[16] however, found water was most effective when the sand particles were moved a distance of 90 miles.

89. Results of Physical Formation.—The physical formation of soils is mainly associated with movement. As a consequence, the particles are broken down, mixed, sorted, churned up again, moved to other parts, re-assorted, and re-deposited. As a result, the material that we now call soil has been derived, in many cases, from unknown sources.

The mineral portion of our present soils was formed possibly

[15] Mackie, W., "The Laws that Govern the Rounding of Sands," *Trans. Edinburgh Geol. Soc.*, 7, pp. 298-311. 1896.

[16] Anderson, G. E., "Experiments on the Rate of Wear of Sand Grains," *Jour. of Geology*, *34*, pp. 144-158. 1926.

ages ago. Since its formation, this mineral matter has undergone, and is still undergoing, change until in many cases it gives little or no indication of its origin. Each of these alterations has and will continue to have a greater or lesser influence on the physical properties and functions. But the mineral portion has been the support of biological activities, and the seat of chemical forces. These in turn have served as very efficient agencies in causing still greater change, a change influenced in many cases by the physical properties of the mass. The continuous march of events causing a ceaseless change in soils is of ever-increasing interest.

CHAPTER 8

SOIL TEXTURE

Texture refers to the solid portion of the soil mass (the soil particles.) It is concerned mainly with the mineral particles. It is defined as follows: *Texture* is a term indicating the size of the individual soil grains or particles, or the fineness or coarseness of the soil mass. As the soil is usually made up of particles of widely varying size, the textural terms express the average effect or the combined effect of all these grain sizes, or they may indicate the predominance (in quantity or in textural effect) of a certain group of grains.

90. Soil Texture in the United States.—Texture is determined by mechanical analysis—a laboratory process of separating the soil into groups of grain-sizes. The United States Bureau of Soils system of mechanical analysis separates the soil into seven grain-sizes or "separates" having the following sizes and names: [1]

Size				Name
2.000	to	1.000	millimeters	Fine gravel
1.000	"	0.500	"	Coarse sand
0.500	"	0.250	"	Sand
0.250	"	0.100	"	Fine sand
0.100	"	0.050	"	Very fine sand
0.050	"	0.005	"	Silt
0.005	"	and below	"	Clay

91. Soil Texture in Other Countries.—Soil investigators in various parts of the world are not in exact agreement regarding the limits of size of the various separates, especially of the smaller-sized fractions. This is due mainly to the large number of different methods of mechanical soil analysis **(95)**. The following table gives the names and sizes of the various fractions obtained by mechanical analysis, according to British and German standards.

[1] For a more extended discussion and description of the various mixtures see *Soil Texture, Texture,* and *Textural Grade,* in the Glossary.

TABLE 5

SOIL TEXTURE (BRITISH AND GERMAN STANDARDS)

(Adapted from Russell, 4th ed., page 98)

British		German	
Fraction	Size of Particles mm.	Fraction	Size of Particles mm.
Fine gravel	3 to 1	Kies	above 2.0
Coarse sand	1 to 0.2	Sand	2.0 to 0.2
Fine sand	0.2 to 0.04	Mo.	0.2 to 0.02
Silt	0.04 to 0.01	or Fein sand	0.2 to 0.06
Fine silt	0.01 to 0.002	Mehl sand	0.06 to 0.02
Clay	below 0.002	Schluff (or staub)	0.2 to 0.002
		or grober Schluff	0.02 to 0.006
		feiner Schluff	0.006 to 0.002
		Schlamm (or ton)	below 0.002

92. The Size of the Particle.—The simplest manner of discussing the soil particle is to assume first that all particles have the same characteristics. Let us assume, for instance, that the particles are spherical. If a sphere one inch in diameter is placed in a one-inch cube, Fig. 4A, the unoccupied space will be 0.4764 cubic inch. If the cube is now filled with 1,000,000 spheres, each 1/100 inch in diameter, packing them so that each tier will rest

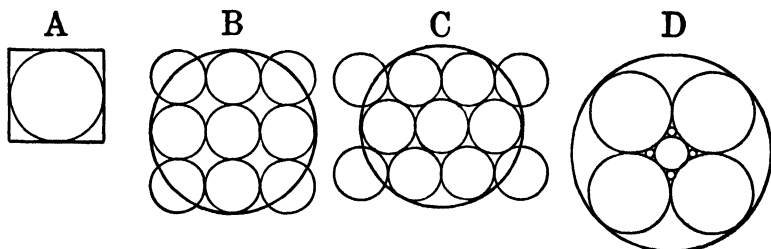



FIG. 4.—Diagrams showing the relationship of various sized particles.

directly upon the tier below, the unoccupied space will still be 0.4764 cubic inch, Fig. 4B. The change in size has not affected the interstitial space. If, however, the tiers are arranged so that the second tier fills the depression in the first tier and thus secures the closest possible packing of the spheres, Fig. 4C, we find that the interspace has been reduced from 0.4764 to 0.2595 cubic inches. If the soil consisted of a mass of uniformly sized spherical particles, the interspacial effect would never be greater than 47.64 per cent nor less than 25.95 per cent.

93. Packing of Particles.—The soil is not composed of uniform particles either in size or shape, therefore the smaller particles are able to pack in the space between the larger. If 1,000,000 spheres 1/100 inch in diameter are placed in such positions that the interspacial effect is 25.95 per cent, and a second set of spheres, of such size that they will exactly fit, are placed in the interspaces, Fig. 4D, it will be found that 6.76 per cent of the space is unoccupied. If a third smaller set of spheres is fitted exactly into the remaining unoccupied spaces, this space is reduced to 1.76 per cent of the entire mass. The process may be continued indefinitely, but will never reach a point where the interspacial effect will be completely eliminated. The interspacial effect of the soil mass, however, cannot be reduced beyond a certain point because plant life requires that a certain portion of the soil mass be free for the functions of the liquid and gaseous states. Neither can it be increased beyond a certain point, else these functions be reduced.

94. The Number of Particles.—The number of particles in the soil mass varies widely. Due to the fact that they are not uniform in size or shape, and vary from quite large to a submicroscopic point, their calculation or estimation is subject to great inaccuracies. The great number of particles in one gram of soil varies from approximately two billion or less in the case of sands to over twenty billion in the case of clays.

95. The Physical Analysis of Soil.—The physical (mechanical) analysis of soils consists of a determination of the amounts of the various sized particles constituting the mass. The object is to obtain information about the size of the ultimate particles of which the soil is composed. Due to the fact that there is always a certain amount of aggregation (cementation) of particles, the use of sieves, especially with the finer particles (fractions), is not practical. The usual process is to separate the larger particles by the use of standard sieves and to accomplish the separation of the smaller particles by suspension methods. The suspension methods are based primarily on Stokes' law.[2] The organic matter is removed by ignition, by boiling with H_2O_2 or, if not in excess, left alone. The aggregates are deflocculated with ammonia and, if lime is present, with hydrochloric

[2] Stokes' Law: When small spheres fall through a column of fluid under the action of gravity, they ultimately acquire a constant velocity. The

acid, agitated, and then treated in various ways to accomplish the separation.[3]

96. Methods of Physical Soil Analysis.—The methods used in the physical (mechanical) analysis of the smaller soil particles are essentially those of suspension in water, and differ from each other merely in the mechanical details of the process, the divisions according to size being based on microscopic measurements. They may be grouped as follows:

I. Separation by Use of Water.

1. Sedimentation and Decantation: This process may be illustrated by the Osborne beaker method[4] in which the agitated soil suspension is placed in beakers, allowed to settle for varying periods, at the end of which time the supernatant liquid is poured into other beakers and allowed to settle. This method is modified in various ways; for instance, by removing the excess soil suspension at stated intervals with compressed air (subsidence method), by pipetting off certain depths of the excess suspension at stated intervals (pipette method), or by repeated decantation and washing (decantation method). In these methods, the separates are collected, the excess water evaporated and the residues dried and weighed.

These methods give the percentage composition of the different separates but show nothing of their relative distribution. This is due to the fact that the soil particles do not have a definite radius, are not spherical, and may be surrounded by a gelatinous material. This objection is overcome by the method of Sven

velocity of fall and the radius of the particle are connected by the equation:

$$V = \frac{2\,gr^2\,(d_1 - d_2)}{9\,N}$$

Where V = velocity of the fall,
r = radius of the particle,
d_1 = density of the particle,
d_2 = density of the fluid,
N = coefficient of viscosity of the fluid.

[3] Robinson, G. W., "A New Method for the Mechanical Analysis of Soils and Other Dispersions," *Jour. Agric. Sci.*, *12*, pp. 306-321. 1922.

Robinson, G. W., "The Form of Mechanical Composition Curves of Soils, Clays, and Other Granular Substances," *Jour. Agric. Sci*, *14*, pp 626-633. 1924.

A. E. A. Sub-Committee, "The Mechanical Analysis of Soils. A Report on the Present Position, and Recommendations for a New Official Method," *Jour. Agric. Sci.*, *16*, p. 12 (1926).

[4] Osborne, *Annual Report Conn. Agric. Expt Sta.*, pp. 141-158 (1886); pp. 144-162 (1887); pp. 154-157 (1888).

Odén,[5] who suspends a counterpoised plate, attached to one arm of a balance, near the bottom of a cylinder containing the soil suspension. By the use of suitable recording apparatus, he is able to secure a distribution curve that shows how the particles are distributed according to size. The method is subject to slight errors due to a flow of liquid which interferes with the free vertical fall of the particles.[6]

2. Elutriation: The elutriator methods make use of the fact that currents of water moving at certain velocities will transport certain sized particles. Usually the water is introduced at the bottom of a specially constructed container and the suspension carried over is collected at the top.[7] This method was modified [8] by the introduction of an agitator to keep the soil particles in motion.[9]

3. Centrifugal Force: Due to the fact that the smaller soil particles remain in suspension for long periods, some indefinitely, and are not influenced by gravity, the centrifugal is used to throw them out of suspension. This method has been perfected by the United States Bureau of Soils [10] and is now used extensively in this country for the physical analysis of soils.

II. Separation by the Use of Air.—The use of air for the separation of the particles is a modification of the elutriation process. The particles are separated in the dry state by an air blast.[11]

97. **Textual Composition.**—The textual composition of the soil mass is determined by mechanical analysis. The percentage

[5] Odén, Sven, "Eine neue Methode zur mechanischen Bodenanalyse," *Internat. Mitt. Bodenkunde*, *5*, pp. 257-311. 1915.
Odén, Sven, "Size Distribution of Particles in Soils and the Experimental Methods of Obtaining Them," *Soil Science*, *19*, pp. 1-36, 1925.

[6] Couts and Crowther, *Trans. Faraday Society 21*, Pt. 2, pp. 1-7. 1925.

[7] The Methods of Nobel and of Schone are described in Wiley, H. W., *Principles and Practices of Agricultural Analysis*, pp. 231-241. 1906.

[8] Hilgard, E. W., *Soils*, p. 91. 1907.

[9] Various methods of mechanical analysis are described in: King, F. H., *Physics of Agriculture* (1907); Wiley, H. W., *Principles and Practices of Agricultural Analysis*, pp. 231-241 (1906); Mosier and Gustafson, *Soil Physics and Management* (1917); U. S. Dept. of Agric. *Bur. of Soils. Bul. 24* (1904), and *84* (1912); Atterberg, *Intern. Mitt. f. Bodenkunde*, *1*, p. 7 (1911), *2*, pp. 312-342 (1912); Williams, *Forsch d. Gebiet d. Agrik-Physik*, *19*, pp. 225-242 (1895); Smolik, *Int. Soc. Soil Sc. Proc.*, *1*, pp. 7-24 (1925); and by Hissink, *Int. Soc. Soil Sci. Proc.*, *1*, pp. 137-157. 1925.

[10] Briggs *et al.*, *U. S. Dept. of Agric. Bur. of Soils. Bul. 24*, 1904. Modified by Fletcher and Bryan. *Ibid.*, *Bul. 84*. 1912. See also Yoder, *Utah Agric. Expt. Sta. Bul. 89*. 1904.

[11] Cushman and Hubbard, *Jour. Amer. Chem. Soc.*, *29*, pp. 589-597. 1907

composition of the different-sized particles determines the soil class.[12] The mechanical analysis of some of the more common soil classes is shown in Table 6. As ten of the main soil classes are composed of sands, silts, and clays, and as these combinations make up the bulk of agricultural soils, it is possible to quickly designate these classes from the results of the analysis [13] by reference to an equilateral triangle, Fig. 5.

TABLE 6

MECHANICAL ANALYSIS OF SOME OF THE MORE COMMON SOIL CLASSES [14]

Fraction / Soil Class	Fine Gravel	Coarse Sand	Medium Sand	Fine Sand	Very Fine Sand	Silt	Clay
Coarse sands...	12	31	19	20	6	7	5
Sands	2	15	23	37	11	7	5
Fine sands	1	4	10	57	17	7	4
Sandy loams...	4	13	12	25	13	21	12
Fine sandy loams	1	3	4	32	24	24	12
Loams	2	5	5	15	17	40	16
Silt loams	1	2	1	5	11	65	15
Sandy clays ...	2	8	8	30	12	13	27
Clay loams	1	4	4	14	13	38	26
Silty clay loams	0	2	1	4	7	61	25
Clays	1	3	2	8	8	36	42

98. The Interpretation of Physical Analysis.—Due to the fact that arbitrary lines are drawn and specific grouping of fractions are made, when in fact none exist in Nature, it is very difficult to interpretate a physical soil analysis and correlate it with plant growth. The broad general results are of value in indicating the general physical properties of the mass, especially the relation of the solid portion to the moisture and air content. When, however, they are combined with other analyses (chemical and biological) in the hand of an experienced investigator, their value is considerably enhanced.

99. Limitations of Physical Analyses.—The above table shows that the clay fraction is the ultimate size of the particle in the physical analysis of soils. This is not so; the clay group

[12] For analyses of the soils of Africa, see Shantz and Marbut (**61**): of Europe, see Glinka, *Die Typen des Boden Bilden* (**61**); of the United States, see *Soil Reports, Field Operations, Bureau of Soils*, and *Soil Reports from the State Experiment Stations*. See also Appendix, pp. 347 to 363.

[13] Davis, R. O. E., and Bennett, H. H., "Grouping of Soils on the Basis of Mechanical Analysis," *U. S. Dept. of Agric. Dept. Circ. 419*. 1927.

[14] Whitney, M., "The Use of Soils East of the Great Plains Region," *U. S. Dept. of Agric. Bur. of Soils. Bul. 78*, p. 12. 1911.

in this case is merely a composite of all those particles smaller in size than silt. The physical analysis makes no attempt to differentiate this grouping further. The moisture film of the soil particle (135) may play some very important rôles, especially as the size of the particle decreases, consequently we may expect that, as the size of the clay particle decreases, it may assume

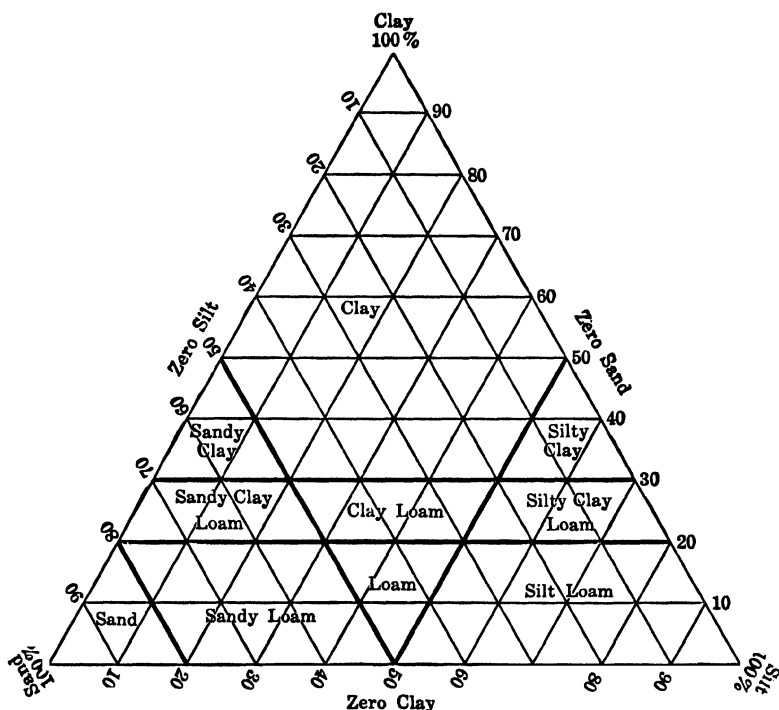



FIG. 5.—Diagram showing ten of the main soil classes in relation to their percentage composition of sand, silt and clay.

additive properties. We may also assume that these smaller particles will have a marked influence on the soil itself. That this assumption is correct is attested by the recent investigations dealing with the smallest particles of soil (the soil colloid), which are playing a very important rôle in soil phenomena.[15] These particles will be discussed in the following chapter.

[15] Davis, R. O. E., "The Interpretation of Mechanical Analyses of Soils as Affected by Soil Colloids," *Jr. Amer. Soc. Agron.*, 8, pp. 293-298. 1922.

The report of the committee on correlative laboratory work of the American Association of Soil Survey Workers [16] shows that there is need for a standardization of methods for various physical determinations of soil functions. For example, the standard methods for mechanical analysis give considerable variation in result due to the personal factor. A given soil was analyzed in several laboratories with the result that the clay content was shown to vary from 15 to 44 per cent, with a corresponding variation in the other classes.

100. Properties of the Soil Fraction.—The physical properties of the various-sized soil particles may differ, especially when the smaller particles are compared with the larger. The particles larger than the colloids and capable of being separated by mechanical analysis have individual properties that influence the soil mass. If the soil mass is fractionated (separated into its individual classes) and the physical property of each fraction determined, the following general properties will be found.

I. Gravel.—Soils consisting of gravel alone are of no agricultural value. If, however, gravel and stones are distributed in small amounts uniformly through the soil mass, especially stiff soils, they may, on the whole, have a beneficial loosening effect, thus facilitating tillage. Because of its bulk, gravel aids in the movement of air and water throughout the soil, it prevents surface evaporation and excessive erosion, and may actually aid in tillage by its loosening effect. Many of our best orchard soils are stony or gravelly. If, however, the gravel is in the form of a bed underlying the soil, it may be very detrimental due to the effect of overdrainage. Gravel does not possess any physical properties except those limited entirely to heat relationships.

II. Coarse Sand.—Like gravel, an excessive amount of coarse sand is very undesirable in soils, as it allows excessive drainage. Not only does the water percolate rapidly downward, but the loose open structure allows rapid evaporation from the surface **(157)**. It has the same physical properties as gravel. A small amount of coarse sand is desirable, especially in heavy soils, because its lack of cohesion enables it to keep the soil mass open and friable. In this manner it may have a marked effect on determining the crop-producing power of the soil. As shown in Table 6

[16] *Report of the Fourth Annual Meeting of the American Soil Survey Assoc. Bul. 5*, pp. 104-105. 1915.

(page 91), the amount of coarse sand in the soil mass is very variable.

III. Fine Sand.—The drainage in fine sands may be excessive as in coarse sands, but such soils may have a certain agricultural value, provided they can be supplied with large amounts of organic matter or with periodic applications of fertilizing materials and be subjected to a fair amount of rainfall during the growing period. We find in this fraction the first evidence of cohesion as exhibited by the formation of a slight crust on the surface after a rain. A fine sandy soil is often spoken of as a "hungry soil" due to its inability to retain the elements necessary for plant growth. Such soils, however, are highly valued in the trucking section of the United States because of their earliness. It frequently happens that, when crops requiring several months to mature are grown, several applications of quickly available fertilizers are required. The low retentive powers of the soil, both for moisture and for the soil-derived plant food elements, coupled with the relatively high precipitation of the areas, makes this practice imperative. When mixed with silts and clays, a certain amount of fine sand in the soil mass is highly desirable as it imparts the necessary open structure and friable condition.

IV. Silts.—Due to the fineness of division and the marked increase in internal surface area, the silt fraction begins to assume additive physical properties due to its relation to the moisture film (101). Silts are intermediate in physical powers between the sands and the clays. They have a greater water-holding capacity than the sands, but less than the clays. Further, their more open structure allows the ready movement of water so essential to plant life. The property of cohesion is marked, but the property of plasticity, so common in the clays, is only in evidence. While the silts have a marked ability to retain moisture, they are not subject to excessive drying and cracking as is clay. The power of absorption is more or less in evidence.

A soil composed entirely of silt is uncommon. While this fraction may constitute as much as 70 per cent of the soil mass, it is usually mixed with other fractions. Its presence in the soil, however, in large amounts is extremely desirable. The fertile loess areas of the United States are illustrative of the agricultural value of this soil fraction.

V. Clay.—Clay [17] is that more or less indefinite fraction between the silt, which is easily determined by mechanical means, and the colloid, which is very difficult of determination. The decrease of the size of the particle and the marked increase in the internal surface area of a unit volume of the material gives a wide area for the introduction or enlargement of its physical powers.

The relation between the clay particle and the soil water is very marked. Not only is the water held as a film on the surface of the particle **(101)**, but a large amount may be absorbed by the particle, thus causing swelling. The swollen particle no longer acts as a solid but assumes an indefinite jelly-like state. The great surface area impedes the movement of water, causing waterlogged conditions in wet weather and a parched condition in dry weather. The property of adhesion, plasticity, tenacity, expansion, contraction, and absorption (both chemical and physical), due to the jelly-like state, is quite marked in this soil fraction. The fineness of the particles allows them to remain in suspension for a long period, in spite of the fact that they have the same specific gravity as the mineral portion of the soil **(168)**. The suspended clays may be flocculated by traces of electrolytes (for instance, lime), causing them to lose temporarily their plasticity and to unite in aggregates that settle and leave the liquid clear. If the flocculating agent is removed, washed out, the aggregates will break up into individual particles with their original properties. On the other hand, the alkalis deflocculate the aggregates or intensify the physical properties of the particle, giving to it distinct colloidal properties such as stickiness, etc.

A certain amount of clay or colloid in the soil imparts binding powers,[18] thus aiding in the structural characteristics of the mass. An excess produces an unfavorable condition. In wet weather, a clay soil is cold and sticky; in dry weather, it dries, bakes, and cracks **(175)**.

[17] From the standpoint of the ceramic industry, the term "clay" may have an entirely different meaning than from the standpoint of the agriculturist. The former is interested in a material which, when well rubbed with water and thoroughly manipulated, will become sticky, plastic, and absolutely impervious to air and water. The latter is interested in every possible means to overcome this impervious condition.

[18] Middleton, H. E., "Factors Influencing the Binding Power of Soil Colloids," *Jour. Agric. Resch.*, 28, pp. 499-513. 1924.

CHAPTER 9

SOIL COLLOIDS

The smallest sized particle recognized in textual soil terminology is the clay group **(90, 91)**, the inference being that any particle smaller than 0.005 millimeter in diameter is clay. While this is true from the standpoint of soil texture, it is not a true picturization of the various sized soil particles upon which may be based a study of the physical and other properties of the soil mass. It has long been recognized that certain soil particles, particularly those defying measurement by ordinary means, possessed properties entirely different from those of larger particles. Further, that these properties appeared to be very closely connected with the crop-producing powers and other functions of the soil mass. As a consequence, the clay fraction has, from the standpoint of scientific accuracy, been divided into a non-colloidal and a colloidal group.

101. The Moisture Film.—All matter is covered with a very thin film of moisture. This moisture is taken from the air by the physical force of attraction and is held by the force of adhesion. The thickness of this film varies with the amount of moisture in the surrounding atmosphere and the characteristics of the material itself. The amount of moisture on any individual particle, therefore, varies according to the characteristics of the particles, the condition (humidity) of the atmosphere, and the surface area of the particle. In the case of large particles, gravels, sands, etc., this film of moisture is relatively unimportant, due to its limited amount. In the case of small and still smaller particles, where the surface area, in proportion to the volume of the particle, is increased, a point is reached where the moisture film may assume such proportions as to be equal (or greater) in volume to the particle itself. When this point is reached, the particle itself has a tendency to partially dissolve in and become a part of the surrounding moisture film, hence the physical and chemical properties of the particle, particularly particles in the

colloidal state, are enhanced by its moisture relationships. The particle does not actually dissolve in the moisture film; rather, it appears to form an emulsion with it that has varying degrees of concentration. For instance, the solid portion of the particle may be combined or be covered with a layer of partially dissolved material that has a more or less jelly-like consistency, and this layer in turn is covered with the unaffected portion of the film.

102. Results of the Subdivision of Matter.—The properties of a mass of small particles can be compared only in a general way with the properties of a mass of larger particles. This is due to the fact that the effect of the moisture film on large particles has little influence, while on small particles it imparts many additive properties. The relation of the degree of subdivision of particles to surface and other phenomena is illustrated in Table 7.

It will be noted that, when a sand particle is subdivided to the size of clay particles, the surface area is increased approximately 1000 times, and that further subdivision may increase this to 1,000,000 times. Theoretically, if a cube one centimeter square was divided into cubes $1\mu\mu$ the resulting mass would have an internal surface area of approximately 1½ acres. The decrease in size of the particle, the increase in surface exposure, and the increasing influence of the moisture film impart additive properties. These additive properties, concerned mainly with the colloidal phase, are very important in determining the physical and other functions of the soil mass.

103. The Colloidal State.—The mineral portion of the soil mass consists of crystalloids, that is, they are made up of orderly arrangements of more or less closely packed molecules. These crystalloids have a certain solubility. They do not go into solution and ionize, for instance, like sodium chloride. Rather, they tend to pass through a number of possible stages. For instance, as the crystalline particle becomes smaller and smaller, its properties become more and more influenced by the solution.[1] It does not react as a true crystalline material, neither does it act as a true solution. In other words, a decrease in the size of the particle has caused a change of state and usually has imparted certain additive physical and chemical properties. The change of state

[1] Wenzel's law states, "The reaction velocity of solids with liquids is proportional to the area of contact."

TABLE 7

THE SUBDIVISION OF MATTER AND RESULTING PROPERTIES[2]

Size of particle	1,000,000 $\mu\mu$	1,000 $\mu\mu$	100 $\mu\mu$	1 $\mu\mu$	0.1 $\mu\mu$
Rel. no. particles	1	10^9	10^{12}	10^{18}	10^{21}
Rel. surface	1	1,000	10,000	1,000,000	10,000,000

	Coarse Suspensions	Colloidal Suspensions	Colloidal Solutions	Molecular Solutions
Appearance	Very cloudy	Turbid	Clear	Clear
Particles observed	With naked eye	With microscope	With ultramicroscope	Cannot be observed
Rate of settling	Quickly or overnight	Slowly or not at all	Do not settle	Do not settle
Particles separated	With filter paper	With clay filter	With ultrafilter	Not by filtration
Diffusion and dialysis	None	None	None or very little	Very high
Adsorption	Low	Considerable	Very high	None
Rate of reaction	Low	Moderate	High	Almost instantaneous
Form on evaporation	Loose powders	Powders and gels	Gels	Crystals
Soil separates	<Sand>↑<Silt>↑<Clay> (50,000 $\mu\mu$; 5,000 $\mu\mu$)	←Suspensoid Clay→	←Ultra Clay→	←Soil Solution→

Limit of microscope (ultra violet light)	100 $\mu\mu$	Diameter pores of hardened filter paper	1,500 $\mu\mu$ to 2,200 $\mu\mu$
Limit of ultramicroscope	10 $\mu\mu$	Diameter pores Chamberlain filter	200 $\mu\mu$ to 400 $\mu\mu$
Limit of ultrafilter	1 $\mu\mu$	Diameter of bacteria	500 $\mu\mu$ to 1,200 $\mu\mu$
Brownian movement starts at	5,000 $\mu\mu$	Diameter 200 mesh particles	74,000 $\mu\mu$.

[2] Truog, E., "The Significance of Soil Colloids in Relation to Plant Feeding and Conservation of Essential Elements," *Jr. Amer. Soc. Agron.*, *17*, pp. 280-285. 1925.

may be directly to a solution or it may be that the reaction velocities are such as to cause a more or less intimate relationship between the particle and water film. It represents a two-phase system. The water itself is one phase, the state of the material is the other phase. In other words, the particle may be in a state partially soluble, partially insoluble, dispersable, and remaining in aqueous suspension under practically all conditions of force. The latter state has been designated as the colloidal state and the particle in this state or capable of assuming this state is spoken of as the *colloid.* The colloid is designated as a suspensoid or an emulsoid according to the intimacy or relationship existing between the particle and the solution itself.

104. Kinds of Soil Colloids.—Soil colloids are formed in the ordinary weathering process and may be either inorganic or organic. Colloidal silica originates from the decomposed remains of plants and from the weathering of rocks. The final state may be colloidal or crystalloidal, depending on the speed of the reaction. If the change is rapid, a colloidal phase may be formed; while if it is slow, quartz crystals may result. If iron compounds are dissolved in water, they may by hydrolysis form colloidal ferric oxide under ordinary conditions. Even difficultly soluble minerals, such as silicates, may under weathering conditions and consequent solution assume colloidal phases.

Organic colloids originate from the decomposition of all sorts of plant and animal remains. They have the properties of starch, gelatin, etc., and vary in all degrees between solids and liquids. Colloidal humus (humic colloid), possessing a slight dialyzability and conductivity, is assumed to occupy a position between a colloid and a crystalloid condition. Microscopic plants and animals are colloids. Their importance, however, is not great in the soil because of their comparatively small mass.

Colloids may be grouped as follows: (1) Materials (gold, platinum, etc.) whose dispersed particles have no appreciable solubility or affinity for water and apparently present a well-defined surface to the surrounding liquid. These are usually referred to as *suspensoids* or *hydrophobic colloids.* (2) Materials (silicic acid, proteins, etc.) whose particles have an affinity for water. Between the particles and the surrounding water, there are all stages of transition or solution. These are usually referred to as *emulsoids* or *hydrophilous colloids.*

105. The Size of Colloids.—The soil colloid is the smallest member of the grouping of soil particles. As it is the state between the crystalloid and the solution, and as this state is influenced first by the surface area of the particle, and second by the individual characteristics of the particle itself, it is evident that there is no clear distinction, from the standpoint of size, between the crystalloid and the colloid. The United States Bureau of Soils[3] has, however, designated the soil colloid as those particles 1/1000 millimeter (designated by the symbol μ) or smaller in diameter. The division is simply arbitrary as all particles smaller than 1μ do not possess colloidal properties, while some particles larger than 1μ are colloidal. There is, however, some justification in setting this limit, which has since been generally adopted because it permits good microscopical control.

106. The Number of Colloidal Particles.—Nothing is known of the number of colloidal particles in the soil. The difficulties encountered in their determination (110) and the extreme variation in the soil make a determination of the total number problematical. The following table showing the diameter, surface area, and number of particles per gram of colloid isolated from seven different soils, will give an idea of the varieties encountered.[4]

TABLE 8

AVERAGE SIZE OF COLLOIDAL SOIL PARTICLES

KIND OF COLLOID	AVERAGE DIAMETER OF COLLOIDAL PARTICLES	SURFACE PER GRAM OF COLLOID PARTICLES	NUMBER OF PARTICLES PER GRAM OF COLLOID DIVIDED BY 10^{12}
	Millimicrons	Square Meters	
Susquehanna	141	15.7	263
Norfolk	129	17.1	322
Sassafras	128	17.0	335
Huntington	111	20.4	505
Marshall	106	21.5	613
Sharkey	91	24.2	960
Fallon	102	21.3	680

107. Properties of Colloids.—In the dry state, the colloids exhibit practically the same physical characteristics as the clays,

[3] Anderson, M. S., Fry, W. H., Gile, P. L., Middleton, H. E., and Robinson, W. O., "Absorption by Colloidal and Non-Colloidal Soil Constituents," *U. S. Dept. of Agric. Bulletin 1122.* 20 pp. 1922.

[4] Anderson, M. S., and Mattson, S., "Properties of the Colloidal Soil Material," *U. S. Dept. of Agric. Bul. 1452.* 1926.

but in the wet state all the properties of clay are intensified. In addition, the colloidal particles become so intimately associated with water that they approach, or may actually enter, the state of a true solution. In the various phases, they may be crystalloids, gels, emulsions, or solutions, depending upon the condition and nature both of the particle and of the solution.

The following is a brief list of some of the more important physical (or physico-chemical) properties of soil colloids.

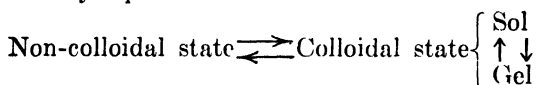
I. Brownian Movement.—When examined under a high-powered lens, colloidal particles have an oscillatory movement. They appear to quiver, dance, or even dart about. The finer the particles, the more rapid their movement. With increase in size, the movement becomes slower and finally ceases when the diameter is about 0.004 mm.

II. Electrical Charge.—As a rule, colloids carry a definite electrical charge. This is proven by the fact that in solutions subjected to a direct electric current, the colloid will usually migrate to one or the other of the two poles. Those moving to the cathode are classified as electro-positive, and those to the anode as electro-negative. Colloidal ferric hydroxide is a representative of the electro-positive group and silicic acid of the electro-negative group. Anderson and Mattson (106) state: "The electrical charge of a colloid is an especially important property, since it largely determines the behavior of the material in the sol condition. The sign and magnitude of charge, however, are greatly affected by the medium in which the colloid is dispersed and by the presence of electrolytes. Variations in the charge of particles can readily be followed by measuring the speed with which the particles migrate under the influence of an electric current. In pure water, the colloidal materials from soils are usually electro-negative. In electrophoresis determinations, the particles move toward the anode with a speed of the same order of magnitude as that of the slower ions, the velocity seldom being greater than 3 microns per second under a potential gradient of 1 volt/centimeter.

"The charge on the particles of soil colloids is markedly affected by the addition of electrolytes to the water suspensions. Electrolytes might be classed in three groups on the basis of their effects on soil colloids: (1) electrolytes which in low concentration increase the negative charge, such as the alkali hydroxides, phos-

phates, and carbonates; (2) those which even in low concentrations reduce the charge without changing the sign, such as most compounds of the alkaline earths; (3) those which are capable of changing the sign of the charge, such as iron, aluminum, and thorium compounds, the basic dyes and acid gelatin. Although a given electrolyte apparently has qualitatively the same effect on all soil colloids, there are quantitative differences in the action of a given electrolyte on different colloidal soil materials."

III. Reversibility.—Most of the changes of the colloidal states of soil particles are probably due to a combination of forces. The ability to change from the non-colloidal to the colloidal state is a function of the material itself and of the surrounding medium. Mere contact with water, however prolonged, is not sufficient to produce this change. The changes of state may be diagrammatically represented as follows:

$$\text{Non-colloidal state} \rightleftarrows \text{Colloidal state} \begin{cases} \text{Sol} \\ \uparrow \downarrow \\ \text{Gel} \end{cases}$$

A colloidal material capable of assuming the various states under varying conditions is spoken of as *a reversible colloid.* If, however, a colloidal material, due to alternate wetting and drying, coagulation, etc., is unable to again assume the colloidal, it is spoken of as *an irreversible colloid.*[5]

IV. Coagulation.—A suspension or emulsion of colloidal particles may be precipitated by the addition of an electrolyte (lime salts, etc.). The suspensoid is more easily precipitated than the emulsoid. Electrolytes vary in their coagulating powers, apparently the higher the valency of the cation of the electrolyte, the smaller is the quantity required to bring about coagulation. The result of coagulation is merely a change from the colloidal to the non-colloidal state. If the agent causing coagulation is removed by washing, etc., the residue may or may not again resume the colloidal state.

V. Adsorption.—The immense internal surface area of colloidal masses, coupled with the reaction velocities at their surfaces, and the fact that the material carries an electrical charge, enables the material to attract water, gases, ions, or materials of opposite

[5] Beaumont, A. B., "Studies in the Reversibility of the Colloidal Condition of Soils," *New York* (Cornell University) *Agric. Expt. Sta. Memoir 21.* 1919.

charge and to repel ions or materials of like charge. If a salt is introduced into the water phase of a colloidal solution, it tends to distribute itself (ionize), but certain ions or materials may often be found locally concentrated at the surface of the colloidal phase. This ability of attraction and holding ions or materials on the surface of the particles is called adsorption.

VI. Absorption.—When a substance is appropriated by some other substance so that it ceases to exist or to be recognized as existing in its original condition, it is said to be absorbed. Thus a portion of the heat radiated by the sun is absorbed by rocks, soils, etc. Liquids, gases, and various substances in solution may also be taken up, absorbed, by other substances and firmly held. Absorption differs from adsorption in the fact that in absorption there is a complete intermingling of molecules resulting in a homogeneous mixture of the absorbent and the absorbed substance. There may not, and in the case of the soil mass there usually is not, any evidence of chemical equivalence even at maximum absorption between the two substances. Absorption in reality is identical with solution; for instance, the absorption of oxygen in water.

When the condition of the soil particle is such that it is markedly influenced by the moisture film (is porous or in a colloidal state), the conditions of adsorption approach those of absorption and it becomes increasingly difficult to distinguish between the two. Because of this difficulty, the term absorption is sometimes used to cover both processes. It should be kept in mind, however, that adsorption refers to surface concentration, while absorption [6] refers to true solution.

VII. Protective Action.—When a reversible colloid is added to the solution of a suspensoid, the coagulation and precipitation of the latter by the addition of an electrolyte is more or less inhibited. It is probable that the emulsoid forms a thin protective envelope round each suspended particle, and thus prevents the

[6] For a summary of soil absorption see: Schreiner, O., and Failyer, G. H., "The Absorption of Phosphates and Potassium by Soils," *U. S. Dept. of Agric. Bur. of Soils. Bul. 32.* 1906.

Patten, H. E., and Gallagher, F. W., "Absorption of Vapors and Gases by Soils," *U. S. Dept. of Agric. Bur. of Soils. Bul. 51.* 1908.

Prescott, J. A., "The Phenomena of Absorption and Its Relation to Soils," *Jour. Agric. Science, 8*, pp. 111-130. 1916.

Anderson, M. S., Fry, W. H., Gile, P. L., Middleton, H. E., and Robinson, W. O., "Absorption by Colloidal and Non-colloidal Soil Constituents," *U. S. Dept. of Agric. Prof. Paper. Bul. 1122.* 1922.

aggregation and consequent flocculation of the particles. This protective action apparently varies with different colloids. It is quite probable that this protective film markedly increases the adsorptive capacity of the soil mass.

108. Summary of Colloidal Properties.—In spite of the fact that soil colloids normally occur as *gels,* their properties have generally been investigated in the *sol* state. This is natural, because, in the present stage of development of colloid chemistry, the properties of sols can be expressed far more quantitatively than those of gels. This point must always be kept in mind when applying the results secured with *sols* to the complex *gel* condition of the soil. In a review of soil colloidal investigations, Marshall[7] compares the properties of inorganic (clay) and organic ("humic matter") colloids, from the standpoint of composition, optical properties, adsorption, coagulation, effect of ions, surface tension, protective action, and electrical double layer. He concludes that "clay is undoubtedly in the main hydrophole in its colloid properties—in its sensitivity to electrolytes it comes between the sulfur sol and the gold sol." The protective action of humic acid places it among the true hydrophiles, while its sensitivity to electrolytes is about the same as the sulfur sol. The evidence is insufficient at present for a comparison with gel systems of more definite composition. Anderson and Mattson[8] summarize (Table 9) the properties of a number of colloids isolated from different soil types.

109. Composition of Soil Colloids.—In a study of the colloidal matter from 45 soils, representing important agricultural types in the United States[9] and eleven Missouri soil types,[10] it was found that a considerable number of the colloids isolated showed almost a constant composition, but different from that of the whole soil. The studies of the wider areas showed the colloids to be higher in alumina, iron, water of combination, organic matter, magnesia, phosphorus and sulphur, and lower in silica than the whole soil. It was found that the colloidal matter

[7] Marshall, C. E., "Some Recent Researches on Soil Colloids," *Jour. Agric. Sci., 17,* pp. 315-332. 1927.

[8] Anderson, M. W., and Mattson, S., "Properties of the Colloidal Soil Material," *U. S. Dept. of Agric. Dept. Bul. 1452.* 1926.

[9] Robinson, W. O., and Holmes, R. S., "The Chemical Composition of Soil Colloids," *U. S. Dept. of Agric. Dept. Bul. 1311.* 1924.

[10] Bradfield, R., "The Chemical Nature of Colloidal Clay," *Jour. Amer. Soc. Agron., 17,* pp. 253-270. 1925.

TABLE 9

SUMMARY OF THE PROPERTIES OF SOIL COLLOIDS[11]

PROPERTY	COLLOID ISOLATED FROM						
	Fallon Loam Soil	Sharkey Clay Soil	Marshall Loam Soil	Sassafras Silt Loam Subsoil	Huntington Loam Soil	Norfolk Fine Sandy Loam Subsoil	Susquehanna Clay Subsoil
Specific gravity in water	2.766	2.718	2.627	2.748	....	2.708	....
Heat of wetting per gram of colloid, in calories	17.5	16.3	14.6	9.8	8.3	7.6	5.3
NH_3 adsorbed per gram colloid, in grams	0.0532	0.0529	0.0415	0.0264	0.0214	0.0266	0.0177
H_2O adsorbed over 30% H_2SO_4 per gram colloid, in grams	0.1776	0.1605	0.1305	0.1143	0.0633	0.0845	0.0518
Imbibed water, per cent	139	123	101	76	60	63	88
Moisture equivalent, per cent	120	94	72	62	64	62	67
Volume increase in water, per cent	150	90	64	64	46	38	82
Volume of floc. per gram of colloid, in cc.	126	110	58.5	38	31.5	31	31
Viscosity of 2% sols.	1.33	1.14	1.23	1.33	1.16	1.12	1.27
Concentration required to give a viscosity of 1.9% by weight	11.2	13.8	13.8	13.1	19.0	16.4	11.9
Methylene blue required to render 1 gram of colloid iso-electric, in grams	0.287	0.253	0.200	0.082	0.100	0.057	0.055
Exchangeable Ca + Mg + K + Na per gram of colloid milli equivalents	1.080	0.687	0.528	0.227	....	0.091	0.087
pH	8.2	6.9	7.1	5.7	7.0	5.3	5.6

[11] The size, area, and number of particles of these colloids are shown in Table 8.

consisted mainly of silica, alumina, iron oxide, and water,[12] with smaller amounts of lime, magnesia, potash, soda, phosphorus, manganese, sulphur, chlorine, and organic matter. In general, the sum of the lime, magnesia, potash, and soda is low when the silica is low, and high when the silica is high. Silica and alumina usually vary inversely. Stoichometrical calculation, however, failed to show that all the silica, alumina, iron, and water was in the proportion to form the commoner hydrated silicates of iron and alumina.

110. Determination of Colloids.—The most common concept of the colloidal material in the soil is that it occurs as a coating or film adhering to the surface of the unaltered mineral grains. The amount of water in the soil does not reach a quantity sufficient to form a suspension of all the colloid present. This suspension must be brought about by a change in concentration, dilution. Unfortunately, when the soil is highly diluted, the colloidal matter does not readily form a suspension, but due to flocculation produces aggregates in different degrees of suspension. These aggregates can only be dispersed by repeated rubbing with water, usually containing a trace of ammonia. The process is very laborious, involving first the separation of the colloidal material from the mineral grains by long shaking, the separation of the larger particles by means of high-powered centrifuges, and the collection of the material itself on very fine clay filters. The actual separation of the aggregates and dispersion of the colloid requires many laborious and careful repetitions of the process.

111. Estimation of Colloids.—A determination of the quantity of colloidal material in the soil mass is becoming more and more important. The difficulties of a direct determination may be overcome by taking advantage of certain properties, particularly that of adsorption, to satisfactorily estimate, if not accurately determine, the amount of colloidal material in the soil. The methods are usually based on the following assumption:

$$\frac{\text{Adsorption per gram of soil}}{\text{Adsorption per gram of colloid}} \times 100 = \text{per cent of colloid.}$$

The materials commonly used are water vapor, dry ammonia gas, and various dyes, etc. Bouyoucos shows that the colloidal

[12] The $\frac{SiO_2}{Al_2O_3 + Fe_2O_3}$ ratio.

content of the soil mass may be estimated by determining the heat of wetting or by the use of the hydrometer.[13]

[13] For a discussion of the various methods used in the estimation of soil colloids and an extensive review of the literature, in addition to references cited above, see:

Bouyoucos, G., "The Heat of Wetting as a New Means of Estimating the Colloidal Material in Soils." *Soil Science, 19*, pp. 153-162. 1925.

Bouyoucos, G., "The Hydrometer as a New Method for the Mechanical Analysis of Soils," *Soil Science, 23*, pp. 343-354. 1927.

Conrey, G. W., "The Determination of the Quantity and 'Quality' of Colloids in Soils," *Committee Report, Amer. Soil Survey Assn., 9*, pp. 1-9. 1928.

Davis, R. O. E., "Colloidal Determination in Mechanical Analysis," *Jour. Amer. Soc. Agron., 17*, pp. 275-279. 1925.

Gile, P. L., Middleton, H. E., Robinson, W. O., Fry, W. H., and Anderson, M. S., "Estimation of Colloidal Materials in Soils by Adsorption," *U. S. Dept. of Agric. Bul. 1193*. 1924.

Gile, P. L., "The Colloidal Content of Soils," *Amer. Soc. Agron., 17*, pp. 270-274. 1925.

See also references given in Chapter 16.

CHAPTER 10

SOIL AIR

As the soil is a mixture of solid, liquid, and gaseous phases, soil air may be considered the state of the latter. As the pore space of the soil is occupied by both air and water, the amount of air in the soil varies with the amount of water. When the soil is in good condition for crop growth, the air content rarely makes up more than 20 to 25 per cent of the volume.

The air of the soil is not by any stretch of the imagination a mere continuation of the atmosphere, but due to its surroundings is influenced by all the complex changes continually taking place. It is, however, influenced by the atmosphere, consequently we will consider the latter as a basis for our discussion.

112. The Atmosphere.—The outer gaseous envelope[1] of the earth—the atmosphere—consists roughly of three constituents: oxygen, occupying 20.94 per cent of the total volume; nitrogen, occupying 78.12 per cent, and argon, occupying approximately 0.94 per cent. With the argon are included such inert gases as krypton, xenon, helium, and neon. In addition, the atmosphere contains varying amounts of aqueous vapor, hydrogen dioxide, ozone, carbon dioxide, ammonia, and other materials such as compounds of nitrogen, hydrogen sulfide, traces of hydrogen, sulfur, organic matter, and suspended solids.

These additional materials are secured from the surface of the earth or by certain disturbances. The aqueous vapor is the result of the evaporation of water. Hydrogen dioxide and ozone as well as some of the nitrogen compounds are possibly formed as a result of electrical discharges. Carbon dioxide is formed as a

[1] When matter is in the gaseous state, it becomes a substance which distributes itself uniformly throughout any space in which it is placed. In this state the molecules forming the gas are separated from one another by considerable distances when compared to the diameter of the molecules. In the gaseous phase the volume available for the use of each molecule is over a thousand times what it is in the liquid state. Gases are capable of mixing with one another in all proportions, frequently without influencing the properties of each.

result of the action of fire, the breathing of animals, liberation from mineral springs, or the decomposition of organic matter by biologic action. Ammonia and hydrogen sulfide are given off by volcanoes, mineral springs, and by biological action. Volcanoes also are active agents in giving off great quantities of gases, sulfur dioxide, and sulfur, while the wind is an effective agent in the distribution of organic matter and suspended solids.

The atmosphere does not always gain at the expense of the earth. Oxygen is always consumed in the process of combustion and usually in respiration. Growing plants, under the influence of sunlight, assimilate large quantities of carbon dioxide. The weathering of rocks also may remove carbon dioxide, while rains may periodically wash the atmosphere of its many accumulations.

In spite of the fact that it is constantly being added to and removed from the atmosphere, the concentration of carbon dioxide is about the same. It is normally present with slight variations to the extent of about three volumes in 10,000. In towns it is higher, in open country lower, but due to wind action does not accumulate at any point. The amount in the atmosphere is calculated as 2200 billion tons. The relations of the amount of carbon dioxide in the atmosphere to climatic features, particularly to glacial formation, has been the subject of considerable discussion.

113. Temperature of the Air.—It is a well-known fact that the temperature of the air decreases with increases in height. The reasons for this are explained in various ways. Humphreys [2] shows that by absorption and radiation the air at the surface of the earth is more heated than at any other level. This air expands and is forced upward by adjacent heavier areas. As it expands and rises against the current pressure it thereby does work at the expense of its own heat. He states, "The decrease of the temperature of the air with increase of height is owing to its dynamical cooling incident to convection which, in turn, is maintained by warming below and cooling above, the warming by absorption and conduction, the cooling by radiation."

114. Effect of Atmospheric Temperature Changes.—The temperature changes of the atmosphere have a marked bearing on the changes of air in the soil. The blowing of the wind is

[2] Humphreys, W. J., "Why the Temperature of the Air Decreases with Increases of Height," *Science*, n. s., 63, pp. 567-569. 1926.

caused by an attempt of the atmosphere to equalize pressure disturbances. Thus the air of a certain section may be heated; it rises, causes a partial vacuum, and air from cooler sections rushes in to overcome the difference in pressure. But gases tend to distribute themselves uniformly through space. Consequently a change of air pressure above the soil causes a change of pressure of the air in the soil and a movement **(120)** takes place.

115. Relation of Soil Cover to Air Temperature.—The kind of soil cover, especially in large areas, exerts a moderating influence upon the temperature of the air. This is expecially true in the case of forested areas. Zon[3] states, "The yearly mean temperature at equal elevations and in the same locality has invariably been found to be less inside than outside a forest. In a level country this difference is about 0.9° F. It increases, however, with altitude, and at an elevation of about 3000 feet is 1.8° F."

116. Relation of Soil to Air Temperature.—Apparently a relation exists between the temperature of the soil and the minimum temperature of the air immediately above. The relationship is a function of the character of the soil, its moisture content, and the amount and character of the vegetal cover. This point is important during that part of the growing season when frosts are likely to occur. Wet soils are cold, hence liable to damage. Light soils are less liable to damage than heavy soils, while soils that are clean of all unnecessary vegetation produce a higher night-air temperature[4] than soils covered with a rank growth.

117. Kind of Space Occupied by the Soil Air.—The amount of pore space in the soil mass is variable **(171)**. Let us now turn our attention to the kind of pore space in this mass and thus secure an idea of the kind of space occupied jointly by the soil air and soil water. We may assume that all water is absent, and assume also (Fig. 4 C, page 87) the most compact packing of a mass of uniform spheres. If planes are passed through eight contiguous centers of these spheres we secure a rhombohedrom (Fig. 6A),[5] from which we may secure a plaster cast (Fig. 6B),

[3] Zon, R., *Forests and Water in the Light of Scientific Investigation*, p. 4. Washington, D. C., 1927. 106 pp.

[4] Haines, E. H., "Influence of Varying Soil Conditions on Night-Air Temperature," *U. S. Mo. Weather Rev.*, *50*, pp. 363-366. 1922.

[5] Fig. 6 adapted from Slichter, C. S., "The Motion of Underground Water," *U. S. Geol. Sur. Water Supply and Irrigation Paper No. 67*. 106 pp. 1902. Also *U. S. Geol. Sur. 19th Annual Rept.*, Part 2, pp. 301-384. 1897-98.

showing the unit element of pore space in such a mass. It becomes evident, therefore, that the kind of pore space is an extremely variable condition, defying any exact description. Further, as the shape of the soil particle rarely assumes the spherical form, the kind of pore space will show even greater variations. These irregularities of pore space in the soil extend in all directions throughout the mass.

King and Slichter [6] assume that, if the soil grains are taken as spherical, of one size and packed in the closest possible

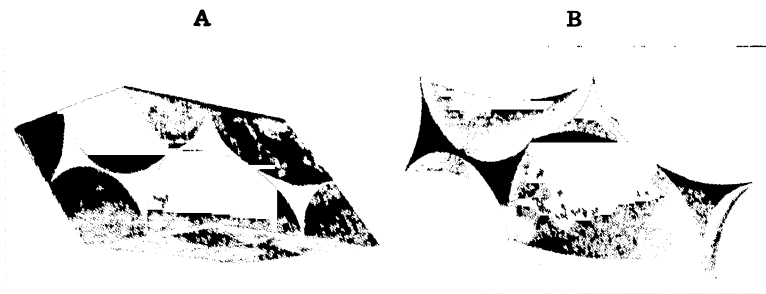



FIG 6.

manner, then the pore space may be regarded as consisting of capillary tubes having an approximately triangular cross section. The mean value (dimension) of the triangular cross section is 0.2118 r^2, where r is the radius of the soil-grain. This triangular pore changes in cross-sectional areas as it follows the surface of the soil grain, passing alternately through maximum and minimum values.

118. The Air-Water Balance.—The kind of pore space in the soil defies description. The soil particle is always covered with a film of moisture **(101)** that, in the case of particles touching each other, forms a wedge or a more or less continuous film throughout the mass. It is known that the amount of water in the soil may vary from the smallest (hydroscopic) to the greatest (saturated) condition.

The gaseous portion of the soil is more mobile than the liquid portion, hence is controlled by the latter. We find therefore

[6] King, F. H., "Principles and Conditions of the Movements of Ground Waters," *U. S. Geol. Sur. 19th Ann. Rept.*, Part 2, pp. 61-294. 1897-98. Slichter, C. S., "Theoretical Investigations of the Motion of Ground Waters," *U. S. Geol. Sur. 19th Ann. Rept.*, Part 2, pp. 301-384. 1897-98.

(Fig. 7), that the air-water balance is entirely a function of the pore space and that as the moisture content increases the air content decreases. Further, due to swelling of the mineral portion of the soil particles, organic matter, etc., still more air is forced out.

FIG 7

119. Relation of Soil Air to Soil Water.—The air of the soil is usually in an approximately saturated condition. The amount of water in the air, however, varies with the temperature. For instance, a cubic meter of air at the point of saturation at 0° C. contains 4.87 grams aqueous vapor, at 15° C. it contains 12.76 grams, and at 30° C. 30.15 grams. As long as the soil contains an appreciable amount of capillary moisture, the moisture content of the soil air (vapor pressure) remains fairly constant. The vapor pressure tends to remain fairly constant until the moisture content of the soil is reduced to a point where it would appear that most of the capillary water has been lost. Below this point the vapor pressure gradually decreases. The vapor pressure [7] is not the same in all soils, for instance, the vapor pressure of a sand with a moisture content of 0.7 per cent

[7] Thomas, M. D., "Aqueous Vapor Pressure in Soils," *Soil Science, 11*, pp. 409-434. 1921.

See also:

Cameron, F. K., and Gallagher, F. E., "Moisture Content and Physical Condition of Soils," *U. S. Dept. of Agric. Bur. of Soils. Bul. 50.* 1908.

Keen, B. A., "The Evaporation of Water from a Soil," *Jour. Agric. Sci., 6*, pp. 456-475. 1914.

Thomas, M. D., "Aqueous Vapor Pressure in Soils. II. Studies in Dry Soils," *Soil Science, 17*, pp. 1-18. 1924.

Puri, A. N., Crowther, E. M., and Keen, B. A., "The Relation between the Vapor Pressure and Water Content of Soils," *Jour. Agric. Sci., 15*, pp. 68-88. 1925.

was found to be 22.737 mm., while a clay loam with 2.65 per cent of moisture gave a vapor pressure as low as 10.65 mm.

120. Effect of Temperature on Movement of Soil Air.—It is known (132) that heat travels through the various soil horizons in waves. This temperature variation has a marked effect on the air movement in the soil. As the temperature rises and moves downward, the soil air expands, and as the volume of the pore space remains constant, the excess is expelled into the atmosphere. When the soil begins to cool, the air content contracts, producing a partial vacuum, and air is drawn from the atmosphere. Thus in general air tends to flow outward from soils during the day and inward during the night, the flow being controlled mainly by temperature.

121. Effect of Temperature on the Rate of Air Flow.—It is a well-known fact that the viscosity of gases, unlike that of liquids, increases with rise of temperature. The velocity of flow of air in soils, therefore, should diminish with rise of temperature. Bouyoucos[8] shows (Table 10) that soils conform to the law of viscosity as far as the order is concerned, but not magnitude. An increase of temperature not only increases the internal friction of the gas, but also causes a swelling and possible re-arrangement of the smaller particles, thus clogging the pores.

TABLE 10

Effect of Temperature on the Rate of Air Flow in Soils

Time Required for 2650 cc. of Air to Pass through Soil Column

Kind of Soil	Temperature of Soil		
	0°C.	20°C.	50°C.
	Minutes	Minutes	Minutes
Quartz sand	1.45	2.00	2.50
Silt loam	11.00	18.30	41.20
Clay	11.50	10 00	33.00
Peat	13.30	20.15	38.40

122. Importance of Movement of Soil Air.—There is no question but that there is a more or less constant movement of air in the soil. The movement is in response to an effort to create a homogeneous composition within the soil, also to establish an equilibrium with the constantly changing atmospheric pressures.

[8] *Mich. Tech. Bul. 22*, pp. 46-50.

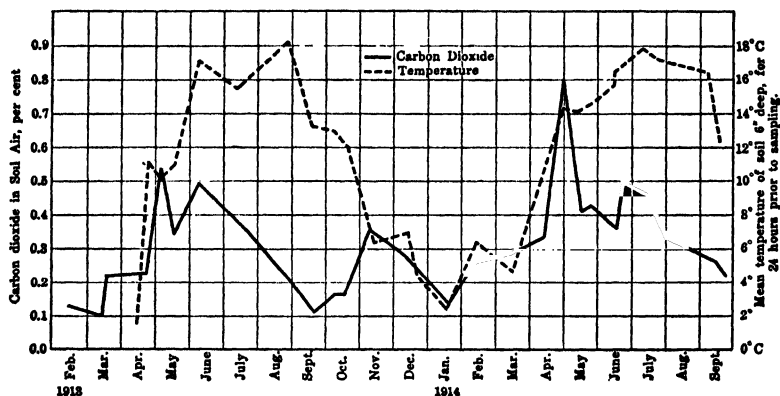



FIG. 8.—Relation of soil temperature to the carbon dioxide content of soil air, Broadbalk unmanured plot, Rothamsted, England. (Adapted from Russell, E. J., *Plant Nutrition and Crop Production*, p. 73. University of California Press, Berkeley, Calif., 1926.)

This movement may extend to great depths and is of great benefit, if not actual necessity, to plant growth, because of the fact that (as in the case of the respiratory system of animals) an accumulation of the gaseous products of biological life is injurious to that life. Thus the movement of soil air aids in the complicated chemical and biological soil processes that are favorable to plant growth.

123. Kinds of Soil Air.—There are apparently two kinds of soil air.[9] The first occupies that portion of the pore space not taken up by water. It is free to move in the soil and is saturated, or nearly so, with water vapor. This air is comparatively rich in oxygen. When this air is removed and suction applied still more, the second kind of air may be drawn off, indicating that it has been largely absorbed by the soil itself or by the soil water. This air differs in composition from the ordinary free soil air in being much higher in carbon dioxide content. These two types of soil air apparently merge in varying proportions.

124. Composition of Soil Air.—The physical functions of the soil have little if any effect on the composition of the soil air. The main changes are dependent upon the chemical and the biological processes, which will be discussed in later chapters. For instance, Fig. 8 shows the relation of soil temperature to the carbon dioxide content of the soil air. Apparently the per cent

variation of carbon dioxide in the soil air follows the same general line as the temperature variation. Actually, the temperature changes produce variations from the optimum for biological soil activities, which in turn affect their ability to produce the carbon dioxide variations. But the ability of the biological soil population to produce these changes is in turn affected by the chemical condition of the soil. The whole process of soil change therefore involves the physical condition, but is dependent on the chemical and biological functions. These changes, however, may markedly affect the physical properties by causing differences in size of particles, variations in structure and texture, color, moisture, and thermal relationships.

[9] Russell, E. J., and Appleyard, A., "The Atmosphere of the Soil, Its Composition, and the Cause of Variation," *Jour. Agric. Sci.*, 7, pp. 1-48. 1915.

CHAPTER 11

SOIL TEMPERATURE

Temperature may be defined as *the thermal state of a body which determines the transfer of heat between it and other bodies.* As heat is a form of energy, and all life activity is an energy expression, it becomes evident that this activity is dependent upon the maintenance of certain temperature relations, above or below which it cannot exist. The growth of higher plants is dependent upon two phases of temperature relations; first, the temperature of the soil, and second, the temperature of the air. The second is essentially a climatic factor. Temperature also is a controlling factor in the chemical function of soils due to the fact that temperature increases accelerate chemical reaction and biological activities.

From the physical standpoint, temperature affects the movement of the soil moisture by causing a change in the surface tension and viscosity of the solution, produces a movement of the soil air by causing a change in pressure, and influences disintegration by expansion and contraction.

125. Source of Soil Heat.—The most important source of soil heat is the sun.[1] The manner in which the soil receives this heat is in the nature of a cycle (Fig. 9). In addition a small amount of heat is derived by the wetting of dry soils **(140)**, by biological action in the decomposition of organic matter **(283)**, by the germination of seeds,[2] and by a temperature gradient in the earth's

[1] The energy of the sun (heat) is transmitted in the form of waves of different lengths (radiation). A heat wave is manifested by the rise in temperature that it causes. The rise is a result of absorption. The efficiency of an object as an absorber of radiation of a given kind or wave length depends upon its nature and not upon its temperature. In the case of the soil the degree of increase depends upon the specific heat of the mass or of the various horizons. The rate at which the heat moves depends on conduction, convection, and on the losses by radiation, to the atmosphere. It must be remembered also that the rate at which heat is given off by an object (lost by radiation) decreases very rapidly with decreases of temperature.

[2] Palladin, V. I., *Plant Physiology*, pp. 218-250. Ed. by Livingston, B. E. (2d Amer. ed.) P. Blackistom Sons & Co. Philadelphia, 1923. 360 pp.

crust from the interior outward.[3] These small amounts, however, may be ignored for all practical purposes.

It is estimated by Lyon and Buckman[4] that "the earth and its atmosphere receive but one two-billionth of the sun's energy." Of this amount probably three-fourths is prevented from reaching the earth's surface by direct absorption in the atmosphere, and by reflection and refraction from clouds, dust particles, etc.,

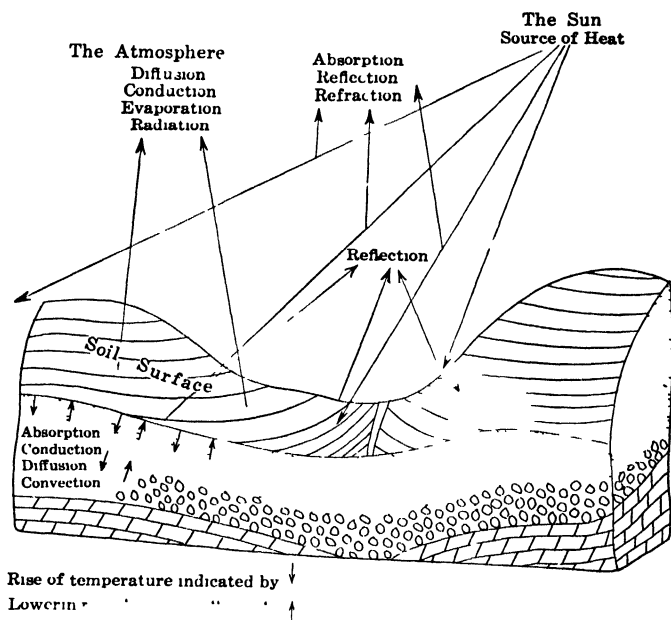



FIG. 9—Diagrammatic representation of heat cycle in soil.

suspended in the atmosphere. An indefinite amount actually reaching the surface of the soil, has no effect, due to its being reflected directly back into the atmosphere.

126. Temperature Cycles in the Soil.—The temperature of the soil is constantly changing. (See Fig. 9.) A rise of temperature in the soil mass is accomplished by the physical processes of absorption, conduction, diffusion, and convection. A lowering

[3] A committee of the British Association (*Brit. Assoc. Rept.*, 1882, p. 72) concludes that an average of "41.4 gramme-degrees of heat escape annually through a sq. cm. of a horizontal section of the earth's substance."

[4] Lyon, T. L., and Buckman, H. O., *The Nature and Properties of Soils*, p. 226. The Macmillan Co. New York, 1926. 588 pp.

of the temperature is accomplished by a reciprocal process involving diffusion, conduction, evaporation (vaporization), and radiation. The rate of this movement is influenced by the soil color, the amount and kind of material covering the soil's surface, and the characteristics of the solid, liquid, and gaseous phases of the soil mass.

127. Effect of Color.—The color of the soil mass has a great influence upon the absorption of heat. A black surface has a tendency to absorb heat waves, a white surface to reflect, hence the former will show a quicker and higher temperature rise than the latter. Thus dark-colored soils, all other factors being equal, will absorb more heat than the light-colored. Bouyoucos [5] found that a series of colored sands after an equal exposure in July had the following temperatures:

Black	40.9° C.	Green	37.1° C.
Blue	40.0° C.	Yellow	35.8° C.
Red	38.5° C.	White	34.6° C.

128. Effect of Slope.—The greatest absorption of heat [6] takes place when the sun's rays strike the soil at a right angle, and the greater the deviation from this angle the less rapid will be the rise in temperature. Consequently the amount of absorption for an area is influenced, first, by the position of the sun in respect to the level of that area; second, by the deviation from the level of the area; and third, by the direction of the deviation. Thus soils in the tropics receive a greater amount of heat than soils in the temperate zones. At a distance north from the equator the soils are warmed more in summer than in winter, and a south slope receives a greater amount of heat than a north slope. Assuming that 100 units of heat are absorbed by a level soil, it was found [7] that a southern slope of 20° on the forty-second parallel, June 21, absorbed 106 units, while a northern slope of 20° only absorbed 81 units.

[5] Bouyoucos, G. J., "An Investigation of Soil Temperature and Some of the Most Important Factors Influencing It," *Mich. Agric. Expt. Sta. Tech. Bul. 17*, p. 31. 1913. 196 pp.

[6] Kimball, H. H., "Total Radiation Received on Horizontal Surface from Sun and Sky at Mt. Weather, Va.," *U. S. Weather Bur. Mo. Weather Rev. 42*, pp. 474-487. 1914. *Ibid.*, *43*, pp. 100-111. 1915. "Variation in the Total and Luminous Solar Radiation with Geographical Position in the United States," *ibid.*, *47*, pp. 769-793. 1919.

[7] Lyon and Buckman, *ibid.*, p. 230.

The influence of slope may be graphically represented as in Fig. 10. It will be noted that the base line ABC receives an equal amount of the sun's rays, but as the elevation C^{1-2-3} is increased in the perpendicular CD, keeping the slopes on both sides the same, the north slope receives a decreasing amount of radiation

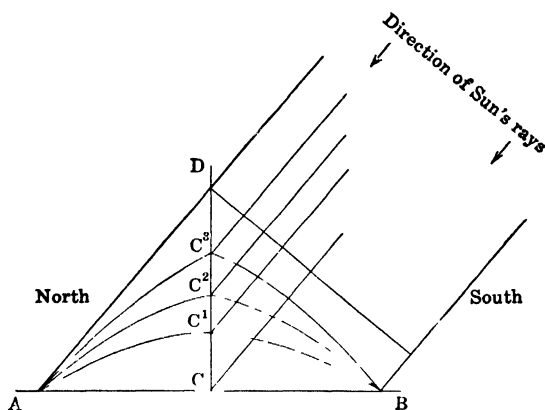



Fig. 10.—Effect of slope upon the amount of heat received.

while the south slope receives an increasing amount. For areas south of the equator the reverse would be true.

129. Effect of Rainfall.—As rainfall naturally comes at a time when the sun is not shining it is difficult to estimate the degree to which the soil is affected. It appears, however, that from early spring to the end of summer, rain cools the soil or stops a warming that would otherwise be expected to occur, thus usually lowering the temperature.[8]

130. Effect of Wind.—There is no definite evidence that wind movements directly influence the temperature of the soil. High winds, however, exert a drying influence, thus increasing the rate of evaporation (157). The removal of water may provide conditions for a greater absorption of heat.

131. Effect of Cover.—Any material covering the soil mass naturally influences radiation, hence cover usually retards the entrance and escape of heat. Its effectiveness depends upon the degree of compaction, a loose material being more effective than a compact mass. The color of the cover, however, may be an

[8] Keen, B. A., and Russell, E. J., "The Factors Determining Soil Temperature." *Jour. Agric. Sci.*, *11*, pp. 211-239. 1921.

important factor in acting as an absorbent of heat.[9] Snow, however, acts as an agent in protecting the soil from very low temperatures.[10]

132. Movements of Soil Heat.—The temperature of the soil has a tendency to lag behind the temperature of the air. This lag is due to a resistance of the heat transfer [11] which is found at the boundary between the substances or particles in contact. Air temperatures follow closely the path of the sun and are usually highest about noon (twelve to one) and lowest some time after midnight (three to five). Thus the air temperature reverses itself in a twenty-four hour period. The soil mass does not have an equal distribution of temperature like the air above it, but, unless frozen, usually has a gradient of temperature at its adjacent depths that reverses itself between day and night, to the depth that the diurnal-nocturnal amplitude of oscillation of temperature extends. For instance, in the morning before sunrise the temperature of the soil is lowest [12] at the surface and increases with depth. As soon as the air temperatures begin to rise, the temperature of the soil surface also rises. The minimum temperature, however, is traveling downward as a wave, gradually losing its force, and lowers the temperature of the various depths as it reaches them. This wave is being followed by the higher temperature wave initiated at the surface. Thus the upper and lower depths have a higher temperature than the intermediate depths. As the higher temperature wave gathers force, due to increased air temperatures, it gradually overtakes the slower moving minimum wave and a point is reached where a gradient is established (usually some time after midday) when the surface soil possesses the highest temperature and the various horizons decrease in proportion to their depth. The lag of penetration of temperature into the soil is so marked that it is necessary to very definitely indicate the depth and the time at which records are made. Cold waves travel through the soil in much the same manner as warm waves.

Taylor [13] shows that the time of maximum soil temperature is,

[9] Stewart, J. B., "Effect of Shading on Soil Conditions," *U. S. Dept. of Agric. Bur. of Soils. Bul. 39.* 1907.

[10] *Mich. Tech. Bul. 26*, p. 122.

[11] U. S. Dept. of Agric. *Bur. of Soils Bul. 59*, p. 48. 1909.

[12] *Michigan Tech. Bul. 26*, p. 53. 1916.

[13] Taylor, E. McK., "Soil Temperatures in Egypt," *Jour. Agric. Sci., 18*, pp. 90-122. 1928.

in the absence of clouds, determined by the time at which the sun reaches its meridian. The time of minimum temperature occurs just before sunrise, provided there are no clouds. The time of maximum and minimum soil temperature in Egypt at various depths is shown in Table 11.

TABLE 11

Maximum and Minimum Soil Temperatures at Various Depths

(Time as hours: 24 = Midnight)

Depth cm.	Maximum Time	Minimum Time	
		July	January
Surface	13.00	5.15	6.45
5	14.45	6.30	8.00
10	17.00	8.00	9.15
15	19.00	9.15	10.45
20	21.00	10.15	12.00
25	23.00	11.15	13.45
30	1.00	12.30	15.00
50	9.00	18.00	20.15

133. Factors Affecting Heat Movement.—There are three modes of heat propagation in the soil, conduction, convection, and radiation. The first is of greatest importance in the warming of the soil mass. Heat conduction is affected by the characteristics of the mass, that is, texture, structure, organic matter, moisture and depth. The horizontal movement is apparently not affected in the same degree as the perpendicular. Bouyoucos[14] found that heat applied to one end of a column of dry sand and a column of moist loam moved as follows:

	1 Inch	2 In.	3 In.	4 In.	5 In.	6 In.	7 In.
Dry sand	2 min.	9 min.	15 min.	27 min.	34 min.	37 min.	40 min.
Moist loam	1 "	6 "	16 "	26 "	35 "	42 "	44 "

The effect of texture, organic matter, and moisture on the time required for a thermometer at 7 inches to show a rise in temperature is shown in Table 12.[15]

Bouyoucos also found that the time required to conduct heat to a depth of 6 or 12 inches in the soil under field conditions varies slightly with the kind of soil, moisture content, and time

[14] Bouyoucos, G. T., *Michigan Tech. Bul. 17*, p. 23.
[15] Bouyoucos, *ibid.*, pp. 18-21.

TABLE 12

HEAT CONDUCTIVITY OF SOILS IN NATURAL AND DRY CONDITIONS

SOIL	NATURAL SOILS UNDER LABORATORY CONDITIONS	DRY SOILS
Sand	27 minutes	38 minutes
Loam	49 minutes	49.7 minutes
Clay	48 minutes	44.2 minutes
Peat	124.5 minutes	55.2 minutes

of year. For instance, gravel and sand required four hours for the heat to be conducted to a depth of 6 inches and seven hours to a depth of 12 inches; loam required six and one-half and nine and one-half hours for similar depths, clay six and nine and one-half hours, white peat required nine hours for the heat to be conducted to the 6-inch depth. At the time the experiment was made the gravel contained 10.45 per cent moisture, sand 11.96, loam 40.7, clay 29.16, and the peat 256.50 per cent. The effect of structure was shown by the fact that an uncultivated soil required four hours for the heat to be conducted to a depth of 7 inches, while a cultivated soil required five hours.

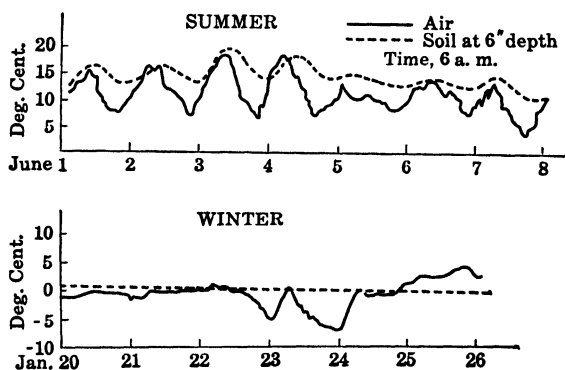



FIG. 11.—Soil and air temperatures in summer and in winter at Rothamsted.

134. Fluctuation of Heat.—The fluctuation of soil and air temperatures for a summer and a winter period are shown in Figure 11.[16]

It will be noted that the fluctuations during the summer differ completely from those obtained during the winter. The tempera-

[16] Keen, B. A., and Russell, E. J., "The Factors Determining Soil Temperature," *Jour. Agric. Sci.*, *11*, p. 213. 1921.

tures of frozen soils frequently show a straight line for long periods. This tends to show that an appreciable amount of heat traverses to the surface from the lower depths and tends to maintain a higher temperature there than would otherwise exist. Convection, diffusion, and radiation are reduced to a minimum, naturally the action of this small source of heat is intensified at this time.

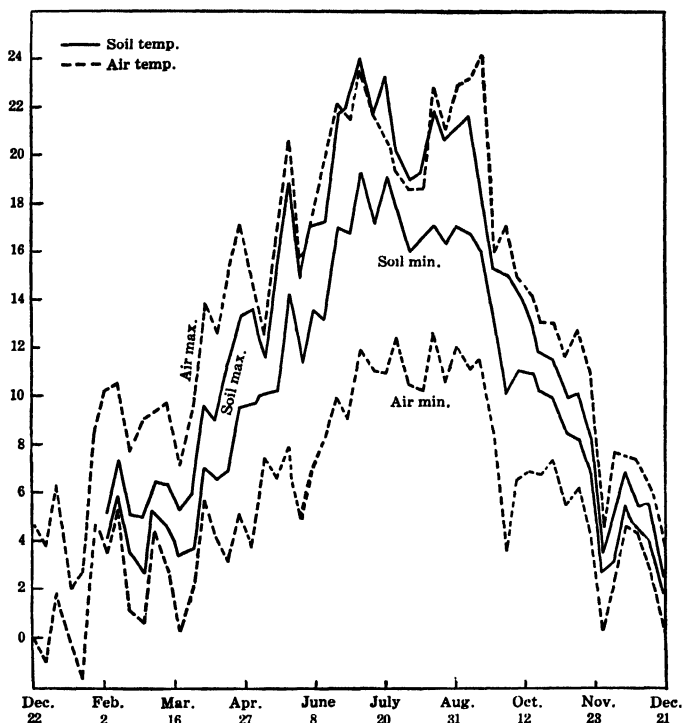



FIG. 12.—Weekly averages of daily minimum and maximum air and soil temperature at Rothamsted

135. Seasonal Variations.—Not only are there daily variations in soil temperature, but seasonal variations as shown in Fig. 12, based on records taken at the Rothamsted Station, December 1913 to December 1914.[17] The chart shows the seasonal variation in the soil at a depth of 6 inches. The period was characterized by a dry January, a wet February and March (7.55″

[17] Keen and Russell, *Jour. Agric. Sci.*, *11*, p. 217.

rain), a dry sunny April with cold winds, a dry cold May with several frosts, a warm June followed by a warm summer (from April to September inclusive there were 1211 hours of sunshine), a wet October, a cold November, and a wet December.

136. Specific Heat.—The specific heat of a substance is the ratio between the heat capacities of equal masses of the substance and of water. In other words, it is the thermal capacity of the mass. The specific heat of water is 1.0. It is defined as the number of calories needed to raise one gram of substance 1° C. Substances with a low specific heat change temperature rapidly.

The specific heat of soil generally refers to the heat capacity of the dry substance and may be determined on the basis of equal weight or of equal volume. The specific heat of all types of dry soil, however determined, is about the same,[18] ranging from 0.1929 for sand to 0.2525 for peat.

The specific heat of the soil mass is affected mostly by changes in its organic matter content due to the fact that the heat capacity of this material is low. In field soils specific heat is important because of the relation it bears to warming up in the spring, and phenomena connected with the moisture content.

TABLE 13

RELATION OF TEMPERATURE TO SURFACE TENSION, VISCOSITY, AND VAPOR PRESSURE OF WATER

Temperature	Surface Tension *	Viscosity *	Vapor Pressure †
0	100.	100.	4.579
10	97.96	73.32	9.210
20	94.32	56.70	17.539
30	91.62	45.12	31.834
40	88.46	36.96	55.341
50	85.52	30.17	92.54

* *Mich. Tech. Bull. 22*, p. 7. 1915.
† Measured in millimeters of mercury. Millard, E. B., *Physical Chemistry for Colleges*, p. 73. McGraw-Hill Book Co. New York, 1921. 411 pp.

137. Effect of Temperature on Moisture.—The effect of temperature changes on the water content of the soil mass is mainly concerned with surface tension, viscosity, vapor pressure, and solution. The relationship of the first three is shown in Table 13. Surface tension and viscosity are important factors in the movement of soil water. Vapor pressure affects the moisture content of the soil air.

[18] *Mich. Tech. Bul. 17*, pp. 10-13.

The solubility of almost all compounds in water increases with increases in temperature. However, it must be remembered that some substances when dissolved in water increase the viscosity, while others may decrease it. The ability of moisture to absorb gases from the soil air is also markedly influenced by temperature.

138. Effect of Temperature on Water Movements.—In studying the effects of temperature on water movement in soils, Bouyoucos [19] found that water, in soils of equal initial moisture content, moved from warm to colder soils. The movement was slight but increased regularly and rapidly with increases in moisture content until a certain moisture content is reached, and then it begins to decrease with further increases in percentage of water. In other words, an increase of temperature decreases the attractive and adhesive forces of the soil for water and decreases the surface tension of the liquid with the result that the colder soils exert a pull depending on the amount of water the warm soil is willing to give up.

It would be expected therefore that the thermal movement of water in field soils would be downward. But there is a greater amount of water in the lower horizons, hence the attractive forces in the lower horizons are more satisfied than those above. As a result the influence of temperature differences on the downward pull is very small in comparison with the upward pull. Hence, during the day, the moisture movement is upward. During the night, nearly all the forces act in a parallel direction favoring an upward movement. Therefore, the thermal movement of capillary moisture in soils is always upward and never downward.

139. Effect of Moisture on Temperature.[20]—The effect of moisture on temperature in the soil mass is to reduce the specific heat, increase conduction, and liberate the latent heat absorbed in drying.

140. Heat of Wetting.—The property of liberating heat on being wetted is generally thought to be a function of the extent

[19] Bouyoucos, G. J., "Effect of Temperature on Some of the Most Important Physical Processes in Soils," *Mich. A. E. S. Tech. Bul. 22*, p. 10, 1916. 63 pp.

[20] The transfer of heat from one particle to another is influenced by the fluid filling the space between them. It is believed (*U. S. Dept. of Agric. Bur. of Soils. Bul. 59*, p. 49) that heat will pass from a soil grain to soil water one hundred and fifty times easier than from a soil grain to soil atmosphere.

and nature of surface. If energy is required to remove water from the soil surface, it is but reasonable to expect that a certain amount of heat of condensation will be apparent when the moist condition is assumed. Heat of wetting is apparently a function confined mainly to the colloidal particle (Table 14). Hence its determination is used as a means of estimating this soil fraction.

TABLE 14

HEAT OF WETTING OF COLLOIDAL MATERIAL AND CORRESPONDING SOIL[21]

SOIL TYPE OR COLLOIDAL MATERIAL	HEAT LIBERATED PER GRAM OF COLLOIDAL MATERIAL	HEAT LIBERATED PER GRAM OF SOIL
	Calories	Calories
Chester loam soil	7.2	1.1
Miami silty clay loam subsoil	11.8	6.4
Sharkey clay soil	16.3	9.6

141. Effect of Temperature on Soil Phenomena.—In addition to its direct influence on crop growth, the temperature of the soil has a marked effect upon all processes. Its influences extend to the gaseous, liquid, and solid soil phases. It influences the diffusion and flow of soil air (121), the movement, flow, and retention of water (137), stimulates or retards the chemical action, and practically controls the biological action.

[21] Anderson, M. S., "The Heat of Wetting of Soil Colloids," *Jour. Agric. Resch.*, *28*, pp. 927-935 (1924). Lit. cit. See also: Patten, H. E., "Heat Transference in Soils," *U. S. Dept. of Agric. Bur. of Soils. Bul. 59* (1909: Bouyoucos, G. J., "Relationship between the Unfree Water and the Heat of Wetting of Soils and Its Significance," *Mich. Agri. Expt. Sta. Tech. Bul. 42* (1918). Lit. cit.

CHAPTER 12

SOIL WATER

There is probably no other factor so important in soil phenomena as water. Many of the physical functions of the soil are dependent on its presence, while the chemical and biological functions connected with plant growth are absolutely controlled by it. Consequently water, more often than any other factor, limits crop production. It enters intimately into the plant as a food, it acts as a carrier of the soil-derived plant food elements, and is the means by which these elements are made available for plant use. Rarely do crops have, during their entire life, the exact quantity of water that serves their needs best; at times the amount is excessive, at other times it is deficient. In some cases the water relationships of soils to plant growth are apparent, in others obscure. The study of the important phases of soil moisture movements therefore has an important bearing in determining the factors influencing the crop-producing power of the soil.

142. Rain.—Rain is the condensed aqueous vapor of the atmosphere. This aqueous vapor[1] is derived by the evaporation of moisture from the surface of the earth. As water evaporates it lifts, by inclusion in vapory vesicles, varying amounts of saline matter, which is afterward deposited in the rainfall. In addition this aqueous vapor dissolves, washes out of the atmosphere **(112)**, and concentrates the other ingredients of the air—gases, organic matter, and suspended solids—and brings them to the ground in rain. When rain falls on the surface of the soil, a part of it runs off directly into streams, a part sinks deeply underground to re-appear in springs, a part is returned to the atmosphere by evaporation, and a part is retained as the ground water of soils. Each of these parts may play an important part in affecting the crop-producing power of the soil. The rain running off into streams acts as a denudation agent and often carries

[1] The term "rain" as used includes all forms of aqueous vapor, rain, snow, hail, etc.

away (erodes) large portions of the surface soil. The part sinking deeply underground may carry away soluble plant food elements. The part returned by evaporation affects the soil temperature, while the part retained by the soil itself is that portion affecting at all times the growth of plants.

The amount of rainfall in different parts of the earth varies widely. As shown in Chart 2, page 339, the United States is rather sharply divided into two great areas on the basis of the average annual precipitation, practically one-half receiving more than 20 inches per year, the other half, with few exceptions, receiving less than that amount. This rainfall, however, is not distributed equally throughout the year. Consequently we find (Chart 7, page 344) that the amount of precipitation during the growing season, "warm season precipitation," is, east of the 18-inch line, usually sufficient for crop growth, while west of that line it may prove to be insufficient. In fact, the main problem west of the 18-inch line of precipitation is moisture control.

143. Water and Vegetation.—Based on conditions of moisture there are three general types of natural vegetation: forest, steppe, and desert. Forests are confined to the better watered portions of the earth's surface or to those regions of moderate rainfall where it is cool and where evaporation is consequently small. Steppes, or open grasslands, are characteristic of regions of light rainfall and warm summers. Deserts, with their scanty vegetation, are the result of extreme dryness. By reason of these climatic and vegetative relations we find zones of different kinds of vegetation, tending to extend around the world, ranging successively from tropical and temperate zone deserts of sand, through steppes, to forests and farming lands, and gradually shading off again, by reason of low temperatures, into arctic deserts of snow and ice.

144. Water and Kinds of Farming.—There are three main types of farming practices in the United States, based mainly on precipitation. First, regions with less than 10 inches of rainfall are wholly unsuitable for cropping without irrigation. Second, regions having 10 to 20 inches may be designated as crop-grazing areas. Where the rainfall is 15 inches or above, dry farming may be practiced with a fair degree of success. Third, areas having more than 20 inches of rainfall are capable of supporting crops adapted to the local climatic condition. The great cereal and

cotton areas of the United States (Chart 9, page 345) have an annual rainfall of 20 inches or more, the major portion of which falls during the growing period.

145. Precipitation in the United States.—"On the basis of precipitation,[2] the United States may be divided into an eastern and a western half, the dividing line being approximately the hundredth meridian, in the vicinity of which the average annual amount is about 20 inches. In general, precipitation is sufficient east of this meridian for successful farming by ordinary methods, but to the westward it is insufficient over large areas for the requirements of crop growth, and irrigation, or special cultural methods for conserving soil moisture, is often employed.

"East of the Mississippi Valley the amount of precipitation varies from about 30 inches in the western upper lake region to 55 or 60 inches along the Gulf coast. In the Great Plains states it varies from about 20 inches in the eastern portion of the Dakotas and 25 inches in central Kansas and western Oklahoma to less than 15 inches in much of Montana and some localities in the west-central and southwestern Plains region. In the Pacific Coast states great differences in precipitation obtain, the average annual amounts ranging from 120 inches in some mountainous districts in western Washington to less than 5 inches in the extreme southeastern portion of California. These localities represent the extremes of moisture conditions found in the United States."

146. Types of Precipitation in the United States.—"There are a number of distinct types of seasonal distribution of precipitation, the most important of which are the Pacific, Plains, and Eastern. The Pacific type is found in the Pacific Coast states and is characterized by a marked winter concentration of precipitation and a summer dryness. In the central and southern portion of the Pacific Coast region less than 20 per cent of the annual rainfall occurs during the six warm months of the year, and in some localities only about 10 per cent occurs during that period. In the Great Plains region, on the other hand, much the greater portion of the annual precipitation is received during the crop-growing season, the percentages ranging from 70 per cent to more than 80 per cent for the period between April 1 and Sep-

[2] "Average Annual Precipitation," *U. S. Dept. of Agric., Weather, Crops, and Markets, 3, No. 2*, p. 31. 1923.

tember 30. In portions of Montana and over small areas of the Dakotas and eastern Colorado the average precipitation for the three winter months is less than 1 inch.

"The Eastern type, broadly speaking, includes the country from the Mississippi valley eastward and is characterized by a comparatively uniform distribution of precipitation throughout the year. However, rainfall during the autumn months is usually lighter than during any other season, particularly in most of the cotton belt, a condition favorable for gathering the cotton crop."

147. Rainfall versus Run-off.—The amount of water falling on the surface of an area is no indication of the amount actually entering the soil. A portion may be absorbed by the soil mass while a portion may be lost as run-off. The amount lost as run-off is extremely variable. It is influenced by the topographical features of the area, the concentration and duration of the rainfall, the soil cover, the condition of the soil surface, and the characteristics of the soil mass. It is difficult to compute the amount of run-off because of the many varying conditions. Mosier and Gustafson [3] state, "It has been estimated that for broad valleys and gentle slopes in open country, a mean annual rainfall of 50 inches gives an annual run-off of about 25 inches, or 50 per cent of the total. Where the rainfall is 40 inches, the run-off is about 15 inches or 37.5 per cent, and where the rainfall is 30 inches, the run-off is about 8 inches or 26.6 per cent." Duley and Miller [4] found that the amount of run-off on a Shelby loam soil is governed by the amount of precipitation falling at any one period and by the soil cover. The run-off from an area in sod was decidedly less than that from an area not cultivated but kept bare. Approximately one-half of the total number of rains were of sufficient intensity or duration to produce run-off.

148. Variability of Water in Soils.—The liquid phase of the soil mass is merely an extension or thickening of the moisture

[3] Mosier, J. G., and Gustafson, A. F., "Washing of Soils and Methods of Prevention," *Ill. Agric. Expt. Sta. Bul. 207*, p. 518. 1918.

[4] Duley, F. L., and Miller, M. F., "Erosion and Surface Run-off under Different Soil Conditions," *Mo. Agric. Expt. Sta. Resch. Bul. 63*. 1923.

See also Okey, C. W., "Run-off from the Drained Prairie Lands of Southern Louisiana," *Jour. Agric. Resch. 11*, pp. 247-297. 1917. Ramser, C. E., "Run-off from Small Agricultural Areas," *Jour. Agric. Resch.*, *34*, pp. 797-823. 1927.

film (101). The amount of water in the soil mass[5] may vary from the small percentage held by adhesion on the surface of individual particles, to an amount occupying the entire pore space. This amount is subject to ever-changing meteorological conditions, to the influence of growing plants and other biological factors, to variations in texture, especially in the clay and smaller fractions, and at times to abrupt changes due to tillage operations. Practically all factors affecting soil water are interdependent—if one of them changes, the remainder will also change in the necessary amount to suit the new conditions. In other words, the water content of the soil mass is extremely dynamic in character.

Keen[6] shows the variability of the water and air content of a heavy loam soil at Rothamsted, England, as affected by various cropping conditions, in Table 15.

TABLE 15

PORE SPACE, WATER CONTENT, AND AIR CONTENT OF CERTAIN ROTHAMSTED SOILS[7]

Soil Treatment	Organic Matter Per Cent by Weight	Volume Occupied in Natural State by		Volume of Water		Volume of Air	
		Solid Matter	Air and Water (Pore Space)	In Normal Moist State	After Period of Drought	In Normal Moist State	After Period of Drought
Arable, unmanured	4.3	66	34	23	17	11	17
Arable, 14 T. manure per annum	10.0	62	38	30	20	8	18
Pasture	13.0	53	47	40	22	7	25

149. Classification of Soil Water.—The liquid phase of the soil mass is generally classified into three forms of soil water, namely, hydroscopic (150), capillary (153), and gravitational (160). This classification is based upon the vapor pressure exerted by the soil water and upon the water-holding capacity of the soil. As the arrangement is based mainly on the relation of plants

[5] Keen, B. A., "The System Soil—Soil Moisture," *Trans. Faraday Soc. 17*, Part. 2, pp. 228-243. 1922.

[6] Keen, B. A., "Agricultural Meteorological Work at Rothamsted," *Jour. Min. Agr.* (Gt. Brit.), *33*, pp. 210-218. 1926.

[7] Adapted from Keen, p. 213. 1926.

to soil water (187), and the separation of the groups is ill-defined, it may be called a practical classification. A suggestion [8] has been made for a more exact, more scientific classification.

This classification, based on dilatometer and freezing-point determinations, arranges the soil water into three groups as follows:

1. Gravitational: Superavailable, unsuited for plants.
2. Free: [9] Very available.
3. Unfree:
   - Capillary-adsorbed—only slightly available.
   - Combined: Water of hydration; Water of solid solution — Unavailable.

It appears, however, that studies [10] on the rate of evaporation of water from soils, the vapor pressure at different moisture contents, the equilibrium relations with seeds, and the freezing point depression due to solid material do not indicate the presence of different forms of soil water. The liquid phase of the soil mass is continuous. Keen [11] shows that the water content of the soil mass is subject to the same law over the whole experimented range. He shows that results secured by various methods

[8] See the work of Bouyoucos, G. J., *et al.*

"The Freezing Point Method as a New Means of Measuring the Concentration of the Soil Solution Directly in the Soils," *Mich. Agric. Expt. Sta. Tech. Bul. 24.* 1915.

"Further Studies on the Freezing Point Lowering of Soils," *Mich. Agric. Expt. Sta. Tech. Bul. 31.* 1916.

"Classification and Measurement of the Different Forms of Water in the Soil by Means of the Dilatometer Method," *Mich. Agric. Expt. Sta. Tech. Bul. 36.* 1917.

"The Freezing-Point Method as a New Means of Studying Velocity of Reaction between Soils and Chemical Agents and Behavior of Equilibrium," *Mich. Agric. Expt. Sta. Tech. Bul. 37.* 1917.

"Relation between the Unfree Water and the Heat of Wetting of Soils and Its Significance," *Mich. Agric. Expt. Sta. Tech. Bul. 42.* 1918.

"Measurement of the Inactive, or Unfree, Moisture in the Soil by Means of the Dilatometer Method," *Jour. Agric. Resch.*, 8, pp. 195-212. 1917.

"A New Classification of Soil Moisture," *Soil Science, 11*, pp. 33-47. 1921.

[9] The free water is that which freezes for the first time at the super-cooling —1.5° C., the capillary-absorbed water is that which freezes finally at the super-cooling of – 4° C., minus the free water. The combined water is that which does not freeze at all, even at the temperature of —78° C."

[10] Parker, F. W., "The Classification of Soil Moisture," *Soil Science, 13*, pp. 43-54. 1922.

[11] Keen, B. A., "A Quantitative Relation between the Soil and the Soil Solution Brought Out by the Freezing-Point Determination," *Jour. Agric. Sci.*, 9, pp. 400-415, 1919; Keen, B. A., "Relations Existing between the Soil and Its Water Content," *Jour. Agric. Sci.*, *10*, pp. 44-71, 1920.

and manipulations are approximate equilibrium values only and do not indicate any break or abrupt change in the physical condition of the soil moisture. The practical classification may therefore be considered as the most logical basis for discussing the water content of the soil mass.

150. Hygroscopic Water.—The moisture film (101) attracted or condensed from the atmosphere and deposited on the surface of the soil particle, or the moisture film remaining on the particle after the excess water has evaporated, may be considered as the hygroscopic water of the soil. It is held very firmly by adhesion or molecular force. The force increases in intensity as the moisture content of the mass decreases.

151. Hygroscopic Coefficient.—An air-dry soil in an atmosphere of low humidity will contain less moisture than a similar soil in an atmosphere of high humidity. A soil in contact with a moisture-saturated atmosphere will, in time, take up hygroscopic water to its full capacity. This point is spoken of as the hygroscopic coefficient. As the vapor pressure of water (137) varies with change in temperature, and as the characteristics of the mass vary in their ability to attract moisture, the hygroscopic coefficient varies accordingly.

152. Amount of Hygroscopic Moisture in the Soil Mass.—Sandy soils usually contain less than one per cent hygroscopic moisture; finer textured soils contain more (Table 16). The amount, however, varies with the amount of organic matter content and treatment of the soil mass (Table 17).

TABLE 16

HYGROSCOPIC COEFFICIENT OF VARIOUS SOIL CLASSES[12]

SOIL CLASS	PERCENTAGE OF CLAY	HYGROSCOPIC COEFFICIENT
Coarse sand	1.6	0.5
Sandy loam	7.5	3.5
Loam	14.4	9.6
Clay loam	22.0	11.4
Clay	32.5	13.2

The amount of hygroscopic moisture in soils is apparently a function of the colloidal content. It has been shown that non-

[12] Briggs, L. J., and Schantz, H. L., "The Wilting Coefficient for Different Plants and Its Indirect Determination." *U. S. Dept. of Agric. Bur. Plant Ind. Bul. 230*, p. 65. 1912.

TABLE 17

HYGROSCOPIC COEFFICIENT VARIATION IN TWO SOIL TYPES [13]

SOIL TYPE	PER CENT OF CLAY	PER CENT OF ORGANIC MATTER	PER CENT OF WATER ADSORBED	PER CENT OF WATER ADSORBED AFTER WETTING AND DRYING 32 TIMES
Dunkirk silt loam surface 3-12″	12.9	5.08	3.97	2.94
Clyde silty clay loam surface 3-12″	20.1	14.54	17.20	10.70

colloidal soils have a low hygroscopic water content,[14] sometimes less than 0.5 per cent, while a soil high in colloids, for instance a clay, also has a high hygroscopic moisture content, often 15 per cent. In fact, the relationship is apparently so consistent that the adsorptive powers of the soil for moisture are sometimes used as a means of measuring the colloidal content (111).

153. Capillary Water.—The most important form of soil moisture is that portion capable of evaporation from the soil mass at ordinary temperatures, but is not in a condition to respond to the action of gravity. This form is spoken of as capillary water. It may be looked upon as an enlargement or thickening of the hygroscopic film, but unlike the latter will not again condense on the particles when once evaporated. In other words, this film is held rather loosely by the soil particle. There is, however, no distinct line of demarcation between the two forms. But the particles in the soil mass are more or less in contact with each other, hence the capillary films are in contact. As the surface of all liquids possesses the property of surface tension and this tends to contract to a minimum area, the point of film contact does not exist as a sharply defined angle; rather it exists as a waist between the two particles. The pull developed by the tendency of the surface to establish an equilibrium and to contract to a minimum area at the coalescence point is sufficient to overcome the force of gravity, hence this form of water may, due to capillary attraction,[15] move in any direction, the direction

[13] Beaumont, A. B., "Studies in the Reversibility of the Colloidal Condition of Soils," *Cornell University Memoir 21*, pp. 501-507. 1919.

[14] Alway, F. J., "Studies on the Relation of the Non-available Water of the Soil to the Hygroscopic Coefficient," *Neb. Agric. Expt. Sta. Res. Bul. 3*, 1913. Also Briggs and Schantz, cited above.

[15] Reinold and Rucker (*Phil. Trans. 177*, Pt. 2, p. 627. 1886.) experimenting with soap bubbles first demonstrated the effect of capillary at-

being toward the area exerting the greatest pull, in other words at the top.

154. The Amount of Capillary Water.—The amount of capillary water or the capillary capacity of soils for water varies widely, being influenced jointly by (1) the surface tension of the solution, (2) the texture and structure of the soil mass, and (3) the organic matter content.

The influence of surface tension has little practical importance. A rise in temperature may decrease the viscosity or the surface tension, thus allowing a freer movement, while a lowering of temperature would have an opposite effect. The presence of salts in solution has a marked influence [16] on surface tension, but the condition of soil water is usually so dilute that the phenomena is of little importance except in those cases where there is a large excess of soluble salts.

The texture and structure of the mass, however, is of the greatest importance. The finer the texture of the mass the higher its capillary capacity, due mainly to the greater internal surface area and close contact of the particles. If sands, for instance, are compacted, more particles will be brought in contact and the capillary capacity increased to a certain degree. Of course further compaction will cause a decrease. But the texture of soils may be modified by flocculation, granulation, etc., causing an enlargement of the pore space and thus affecting the capillary capacity. In the case of clays the effect is to increase it. Bouyoucos [17] shows that ordinary clays will hold as much as 75 per cent of water as compared with 20 per cent in some coarse sands. This function of the soil mass appears to be directly associated with the size of the particles and the organic matter content. The smaller particles, particularly the colloids, may hold large amounts of water.

Organic matter, due to its porous and absorptive nature, has a tendency to markedly increase the capillary capacity. For in-

traction which may be illustrated as follows: If a row of equal-sized wet spheres touching each other are placed in a vertical position, the wet coating will drain downward and drip. When equilibrium is established, the curvature of the annular ring of water between adjacent spheres will diminish, and the actual volume of this ring will increase from top to bottom of the row.

[16] Karraker, P. E., "Effect on Soil Moisture of Changes in the Surface Tension of the Soil Solution Brought About by the Addition of Soluble Salts," *Jour. Agric. Resch.*, *4*, pp. 187-192. 1915.

[17] Bouyoucos, G. J., "The Effect of Colloidal Content upon the Physical Properties of Soils," *Jour. Amer. Soc. Agron.*, *17*, pp. 285-294. 1925.

stance, the capillary capacity of peat may be as high as 400 per cent. When organic matter is wetter it tends to swell, thus affecting the soil structure.

The variation [18] in the capillary capacity of soils and the influence of texture and organic matter is shown in Table 18.

TABLE 18

COMPOSITION AND PHYSICAL PROPERTIES OF WESTERN SOILS AS RELATED TO MOISTURE

SURFACE SOILS	ORGANIC MATTER % *	TOTAL NITROGEN %	HYGROSCOPIC COEFFICIENT %	MOISTURE EQUIVALENT % †	MAXIMUM WATER CAPACITY % §
Silt loam, loess, Lincoln, Neb.	4.93	0.244	10.2	27.8	60.9
Sandy land, Imperial, Neb.	1.22	0.077	3.3	7.9	34.2
Black adobe, Douglas, Ariz.	2.22	0.088	12.9	25.8	60.3
Red loam, Cuerve, N. Mex.	1.07	0.072	10.0	19.2	49.0
Gray desert sand, Palm Springs, Cal.	...	....	1.1	2.8	27.0

* Organic Carbon × 1.724.

† The moisture equivalent is the moisture left in a previously saturated soil after subjecting it to a constant centrifugal force equivalent to 1000 times the force of gravity for a period of thirty minutes. The soil is placed in perforated cups and centrifuged.

See Briggs, L. J., and McLane, J. W., "The Moisture Equivalent of Soils," *U. S. Dept. of Agric. Bur. of Soils Bul. 45*. 1907. For a criticism of this method see Thomas, M. D., and Harris, K., "The Moisture Equivalent of Soils," *Soil Science, 21*, pp. 411-424. 1926.

§ Hilgard Method; see Hilgard's *Soils*, p. 209.

155. Movement of Capillary Water.—The movement of capillary water is mainly a function of surface tension **(153)**, but this function operates in a mass whose pore space **(171)** is exceedingly variable and exists as a series of more or less broken conduits, extending in all directions. The movement of moisture in the soil mass depends therefore on the kind and condition of the material, but for a given structure, will depend on the moisture gradient, the moisture density and the characteristics of the mass. It is obvious, therefore, that the studies of water movements be grouped under two headings; the theoretical and the actual.

156. Theoretical Movement of Capillary Water.—In 1898 Briggs [19] showed that the underlying physical factors concerned

[18] Alway, F. J., and McDole, G. R., "The Relation of Movement of Water in a Soil to Its Hygroscopicity and Initial Moistness," *Jour. Ag. Res., 10*, pp. 391-428. 1917.

[19] Briggs, L. J., "The Movement and Retention of Water in Soils," *U. S. Dept. of Agric. Yearbook 1898*, pp. 399-404. Briggs, L. J., "The

in the movement of capillary moisture were the surface tension, the coefficient of viscosity of the liquid, and the geometrical configuration of the three-phase (163) soil mass. Consequently, the function of the moisture density [20] may be regarded as a theoretical potential under controlled conditions. But a slight change in the structure or other factors may appreciably change the value of the potential. To overcome this condition Gardner [21] derives a capillary transmission constant based on theoretical considerations, from which he calculates that, excepting the influence of gravity, approximately 12 inches of water may be available from a 12-foot water table in a period of thirty days. Later [22] certain assumptions are made regarding the movement of water in soils and formulæ presented to include the various factors affecting the several conditions.

Keen [23] calculates the capillary rise of water in an ideal soil

TABLE 19

CAPILLARY RISE OF WATER IN AN IDEAL SOIL

Fraction	Diameter of Particle in mm.		Capillary Rise in cms.		Average Rise in Ft.
	Maximum	Minimum	Maximum	Minimum	
Fine gravel	3	1	5	15	1/3
Coarse sand	1	0.2	15	75	1½
Fine sand	0.2	0.04	75	375	7½
Silt	0.04	0.01	375	1500	31¼
Fine silt	0.01	0.002	1500	7500	150
Clay	0.002	....	7500	....	150 upward

Mechanics of Soil Moisture," *U. S. Dept. of Agric. Bur. of Soils. Bul. 10.* 1898.

[20] Buckingham, E., "Studies on the Movement of Soil Moisture," *U. S. Dept. of Agric. Bur. of Soils. Bul. 38.* 1907.

[21] Gardner, W., "The Capillary Potential and Its Relation to Soil Moisture Constants," *Soil Science, 10*, pp. 357-359. 1920. Gardner, W., "A Capillary Transmission Constant and Methods of Determining It Experimentally," *Soil Science, 10*, pp. 103-126. 1920. The calculations are long and involved, hence the reader is referred to the original article for details.

[22] Gardner, W., and Widtsoe, J. A., "The Movement of Soil Moisture," *Soil Science, 11*, pp. 215-232. 1921.

See also: Haines, W. B., "Studies in the Physical Properties of Soils." (1) "Mechanical Properties Concerned in Cultivation," *Jour. Agric. Sci., 15*, pp. 178-200. 1925. (2) "A Note on the Cohesion Developed by Capillary Forces in an Ideal Soil," *Jour. Agric. Sci., 15*, pp. 529-535. 1925 (3) "Observations on the Electrical Conductivity of Soils," *Jour. Agric. Sci., 15*, pp. 536-543. 1925. (4) "A Further Contribution to the Theory of Capillary Phenomena in Soil," *Jour. Agric. Sci., 17*, pp. 264-289. 1927.

[23] Keen, B. A., "A Note on the Capillary Rise of Water in Soils," *Jour. Agric. Sci., 9*, pp. 396-399. 1919.

in which the grains are all of one size, spherical and packed in the closest possible manner, and obtains the results shown in Table 19. Of course these figures are never attained in an actual soil, but are of decided value as a starting point for scientific studies of water movements.

157. Evaporation.—The necessary supply of available water for crop production cannot be measured by the rainfall and by the run-off, without knowing the evaporation rate. This rate from a free water surface is decidedly variable and may be from 24 to 72 inches in different parts of the United States.[24] Its influence on plant growth may be illustrated as follows: A strip of short grass extends from Montana to Texas, limited on the west by drought and on the east by competition with other grasses. In Montana the annual rainfall is 14 inches, while in Texas it is 21. The difference of seven inches in rainfall represents the additional amount of rainfall needed to offset the increased evaporation. In recognition of this fact the term "effective precipitation" has been coined.

When water is lost from a soil by evaporation, it passes off in the form of vapor. Only a certain amount will vaporize and a certain amount will be retained **(150)**. In a more or less saturated soil, the moisture vaporizes freely at first from the surface and less freely as the moisture content is reduced. There is a gradual slowing up of the process until a point is reached where the surface evaporation[25] from the film surrounding the particle is controlled by the forces of adsorption and absorption. Hence the rate of evaporation and the limit of evaporation become a function mainly of size and characteristic of the particle, of air temperature and movement, of soil temperature, and of the condition and kind of soil cover.

158. Rate of Evaporation.—Under field conditions evaporation takes place almost entirely at the surface. The rate of evaporation is controlled by two factors, the internal or soil factor, and the external or climatic factor. The internal is a direct result of capillary movement[26] and is influenced by the amount of moisture

[24] Briggs, L. J., and Belz, J. O., "Dry Farming in Relation to Rainfall and Evaporation," *U. S. Dept. of Agric. Bur. of Plant Ind. Bul. 188*. 1910.

[25] Keen, B. A., "The Evaporation of Water from Soil," (1) *Jour. Agric. Sci.*, *6*, pp. 456-475. 1914. (2) *Jour Agric. Sci.*, *11*, pp. 432-440. 1921.

[26] Fisher, E. A., *Jour. Agric. Sci.*, *13*, pp. 121-143, 1923; *Jour. Agric. Sci. 14*, pp. 126-132. 1924.

in the soil, the rate at which this moisture moves, and by any factor influencing it in reaching the surface. Thus evaporation is increased with increases in water content, but the increase is not so great with higher percentages as with the lower.[27] It is usually higher from fine particles than from coarse, and may be reduced by mulches, dry soil, organic matter, etc., or by dissolved salts in high concentration. On the other hand, compacting the surface apparently increases evaporation.

The external factors are mainly climatic. It is greater in direct sunshine than in shade, is greater in an atmosphere of low humidity than in a humid, is increased with increases of temperature, and is greatly increased with increases in wind velocity until a velocity of approximately 15 miles per hour is reached, after which the evaporation rate is not markedly increased.

The internal factors are apparently controlled to a marked degree by the soil colloids. Keen (157) found that evaporation in soils low in colloids could be explained by the known laws of evaporation and diffusion. Soils high in colloidal content did not exhibit the evaporation phenomena, but when these soils were ignited and the colloidal properties destroyed, the differences disappeared.

In a study of factors affecting evaporation of water from soils, Fisher [28] concludes that the factors affecting the rate of loss from a drying system fall into two groups, (1) the drying system itself, and (2) the environmental conditions. The character of the drying system itself appears to be of greater importance than the environmental conditions in determining the type of drying curve. If the movement of moisture or vapor throughout the mass is regular and uniform, the drying capacity may be expressed by curves that may be duplicated. When, however, the movement is slow and irregular, as in the case of clays or heavy soils, the rate curves assume various shapes and replication becomes difficult.

159. Actual Movement of Capillary Water.—Capillary water may move in any direction, but due to gravity it moves with greater facility downward. The movement depends upon the characteristics of the soil, the organic matter content, the tem-

[27] Harris, F. S., and Robinson, J. S., "Factors Affecting the Evaporation of Moisture from the Soil," *Jour. Agric. Res.*, 7, pp. 439-461. 1916.

[28] Fisher, E. A., "Factors Affecting Evaporation of Water from Soil," *Jour. Agric. Sci.*, 17, pp. 407-419. 1927.

perature, any substances in solution, and the height of the water table. If a column of soil is placed in a free water surface, the water moves upward by capillarity. The movement at first is rapid and gradually slows down. The rate varies for different soils. Mosier and Gustafson [29] show (Table 20) the rapidity of movement in different types of soil.

TABLE 20

UPWARD MOVEMENT IN INCHES OF CAPILLARY WATER IN DIFFERENT SOILS

	SAND	CLAY LOAM	WHITE SILT LOAM	PEAT
1 hour	7 5	2 5	4.0	2.6
1 day	9.2	9.0	16.7	5 5
10 days	10 7	18.5	41.6	6.1

Harris and Turpin [30] found that the rise of moisture from soils of varying fineness when used either as water sources (wetted and placed in contact with drier soils) or as water absorbers varied inversely with the fineness and that the most rapid rise was soon after being placed in contact with the water. Also that the movement was nearly twice as great when the initial percentage of moisture was about 15 as with 5 or below. In other words, a soil with a high initial percentage of moisture will come to an equilibrium sooner than a drier one, but if given time the drier soil will absorb a greater quantity of water through a long distance either upward or downward than a wet one. The capillary water is not distributed [31] at a rate uniformly decreasing with the distance above the water table but irregularly. In most cases the maximum amount is found several inches above the water table, while the average percentage is found about three-fifths of the height. The determination of capillary rise of water in tubes through soil masses from a free water table is apparently affected by the cross-sectional area of the column under consideration.[32] Generally large columns (up to 16 square inches) show a greater rise in a given time than small columns.

[29] Mosier, J. G., and Gustafson, A. F., *Soil Physics and Management*, p. 207. J. B. Lippincott. Philadelphia, Pa., 1917.

[30] Harris, F. S., and Turpin, H. W., "Movement and Distribution of Moisture in the Soil," *Jour. Agric. Res.*, *10*, pp. 113-155. 1917.

[31] McLaughlin, W. W., "The Capillary Distribution of Moisture in Soil Columns of Small Cross Section," *U. S. Dept. of Agric. Bul. 1221*. 1924.

[32] Wadsworth, H. A., and Smith, A., "Some Observations upon the Effect of the Size of Container upon the Capillary Rise of Water through Soil Columns," *Soil Science*, *22*, pp. 199-212. 1926.

The actual movement of capillary water is markedly affected by the colloidal content.[33] For instance, water rises at a faster rate in sands than in clays. Undoubtedly the principal cause for this difference is due to the swelling of the colloidal content of the clay which tends to constrict or close up the capillary pores. The surface tension of such organic liquids as ether, benzol, kerosene, etc., is less than water. If columns of dry clay soil are placed over them they will be attracted and rise faster and further in a short time than water because they are not imbibed. If sand is used instead of clay the water will rise faster than the organic liquids If longer periods of time are allowed, the water will rise further in the colloidal soils than will the organic liquids, due partly to the greater attraction and adsorption that colloids have for water and partly to the ability of the finer particles, having a greater number of interstitial angles, to support a higher column of liquid. The actual movement of capillary water in soils is of great practical significance as it is this water that supplies plant needs. A soil may contain enough water to supply plant needs, but it may not move fast enough through the soil to replace the amount removed by the roots. An excellent illustration of this fact is in an excessively drained peat area. Therefore the distribution of water in the different soil levels may be the controlling factor in crop production.[34] For instance, the average moisture content of a whole foot section may indicate a fair amount, but the upper 3 or 4 inches may be too dry to permit germination, while at another time this portion may be optimum and the lower section be too dry to permit the penetration of roots. This condition may readily be extended to deeper soil levels; for instance, under dry farm conditions one crop may deplete the soil moisture of a certain depth to such an extent that a long period, six months to over a year, is required to again establish an equilibrium.

160. Gravitational Water.—If the amount of capillary water in a soil mass is increased, a point will be reached where the capillary effects are more or less nullified, and free water will appear in the air spaces. As in the case of the division between

[33] Bouyoucos, G. J., "The Effect of the Colloidal Content upon the Physical Properties of Soils," *Jour. Amer. Soc. Agron. 17*, pp. 285-294. 1925.

[34] Alway, F. J., and McDole, "Variation in the Moisture Content of the Surface Foot of a Loess Soil as Related to the Hygroscopic Coefficient," *Jour. Agric. Resch., 14*, pp. 453-480. 1918.

hygroscopic and capillary water there is no distinct line of demarcation. The forces controlling capillarity are satisfied; consequently the excess water is subject to the force of gravity and moves downward.

161. The Water Table.—As the gravitational water moves downward through the soil mass, it meets at various levels an impervious layer that causes it to collect, forming a saturated area. The upper level of this saturated area is called the water table. The height of this water table is influenced by the character and slope of the surface material, the form of the impervious layer, the altitude and distance of the nearest drainage channel, and the amount of rainfall. Fine material and large rainfall tends to make the water table stand high within the hills and elevated places, while coarse material and low rainfall would cause a low water table. The height of the water table is subject to constant variation, dependent upon the varying relations between rainfall, evaporation, and barometric pressure. Thus in dry years the height of water in wells is considerably lowered. A lowering of the barometer causes an increased flow of water into springs and wells, a phenomena of common occurrence.

A change of one inch in height of the barometer corresponds to a change of pressure of about 1 foot of water. A lowering naturally releases the pressure. Sometimes in the West, just before a storm, a low barometer will cause wells to blow, that is, large quantities of air may be forced out with a loud roar.

162. Movement of Gravitational Water.—The water collected at and below the water table by the force of gravity moves slowly by the same force into the neighboring drainage channels, springs, streams, lakes, etc. (Fig. 13A). The rate of flow is usually very slow, being influenced by the steepness of the slope and the character of the material through which it passes (see Table 21).

TABLE 21

VELOCITY OF GROUND WATER IN MATERIAL OF DIFFERENT GRADES WITH A SLOPE OF TEN FEET PER MILE

MATERIAL	FEET PER YEAR
Fine sand 0.2 mm. diameter..............	52.8
Medium sand 0.4 " "	216 0
Coarse sand 0.8 " "	845.0
Fine gravel 2 0 " "	5386 0

In other words, it appears that the return flow of ground water to the water courses is by means of diffused and almost imperceptible seepage. On the other hand, it is not always free in this movement. As illustrated in Fig. 13B, the water table may

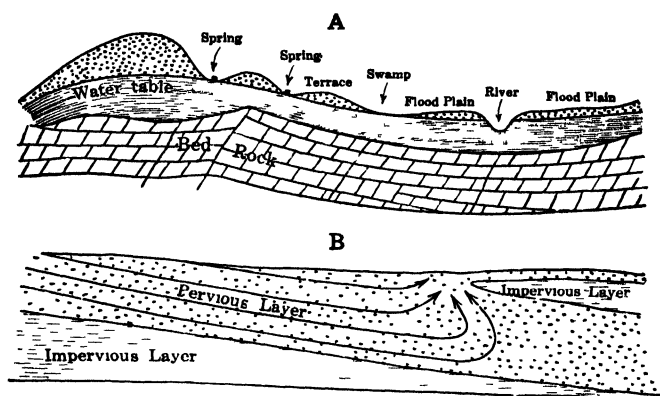



FIG. 13.—Illustrating gravitational water movements. (Adapted from Schlicter, C S, *The Motion of Underground Water.*)

be forced to the surface by an intervening impervious stratum, oftentimes in an apparently level surface.

Keen [35] shows the average amount of water draining (percolating through 60 inches of heavy loam soil at Rothamsted (England) for a 45-year period in Table 22. He states, "In the

TABLE 22

MONTHLY AMOUNTS OF DRAINAGE THROUGH 60 INCHES OF SOIL
Average of 45 years (1870–1, 1914–5)

MONTH	RAINFALL IN INCHES	DRAINAGE IN INCHES	DRAINAGE PER CENT
September	2.30	0.64	27.8
October	3.27	1.69	51.8
November	2.81	2.04	72.6
December	2.78	2.29	82.4
January	2.31	1.97	85.3
February	2.01	1.49	74.1
March	2.04	1.13	55.4
April	1.87	0.55	29.4
May	2.07	0.50	24.2
June	2.44	0.65	26.6
July	2.58	0.60	23.3
August	2.66	0.62	23.3

[35] Keen, B. A., "Agricultural Meteorological Work at Rothamsted," *Jour. Min. Agr.* (Gt Brit), 33, pp. 210-218, 1926.

summer months the soil is dry and little of the rainfall appears as percolation water. The rest is held by the soil and in large part evaporates again. As the winter approaches, evaporation is much reduced and the moisture content increases toward its saturation value, until in the winter months percolation forms a high percentage of the rainfall."

CHAPTER 13

PHYSICAL PROPERTIES OF THE SOIL MASS

The soil mass consists of many solid particles of various size and shape. The particles are covered with a moisture film **(101)** of various degrees of thickness **(150, 153, 160)**. The moisture content may or may not fill the interspaces. When it does not, the remaining pore space is occupied by the soil air.

163. Phases of the Soil Mass.—The soil mass may exist as a two-phase system (solid and liquid), or as a three-phase system (solid, liquid, and gaseous).

164. Properties of Soil Phases.—The properties of the gaseous phase are concerned mainly with thermal relationships, for instance, expansion, contraction, and diffusion. The properties of the solid phase, *in the dry state*, are mainly concerned with thermal relationships, for instance, absorption, conduction, convection, contraction, expansion, and radiation. These properties are affected and their functions complicated by the ability of the solid particles to attract moisture. The properties of the liquid phase include all the properties of the other two phases and in addition many other properties characteristic of water; for instance, dispersion, surface tension, evaporation, vapor pressure, etc.

165. Properties of the Soil Mass.—The soil mass not only reflects the individual properties of each of the phases but, due to the combined influence of these properties, the mass assumes many additive properties. As a result, the properties of the mass affecting its physical characteristics may be listed as follows:

Absorption (**107,** ***VI***)
Adhesion
Adsorption (**107,** ***V*****, 211**)
Aggregation
Attraction (**101**)
Binding power
Cementation (cemented)
Coagulation (**107,** ***IV***)
Cohesion
Compaction (compact)
Conduction
Contraction (**174**)
Convection
Diffusion

Dispersion
Elasticity
Evaporation (157)
Expansion (173)
Flocculation
Granulation
Heat of wetting (140)
Imbibition
Moisture holding
Percolation
Permeability
Plasticity (plastic)
Puddling (puddled)
Radiation
Saturation
Surface tension (137)
Swelling (173)
Tenacity (tenacious)
Vaporization (157)
Vapor pressure (137)
Viscosity (137)

Terms not followed by a section number are defined in the Glossary.

The functions of these properties are governed by the state of the solid, liquid, and gaseous phases of the mass. They are usually quite complex and in many cases are so involved that it is difficult to distinguish the cause of a certain phenomenon. Some of these properties are primarily physical in nature, a few are primarily chemical, while the majority have decided physicochemical characteristics. A few of the properties are common to either dry or moist soils. The majority of the properties, however, are evidenced only in the presence of varying amounts of water, the reason being that the addition of moisture introduces a state having great physical and chemical powers and a free bounding surface.

166. Surface Area of Particles.—It has been shown (Fig. 4, A and B) that one sphere 1 inch in diameter and one million spheres 1/100 inch in diameter occupy the same space in a 1-inch cube (92). In spite of the fact that the interstitial space has not been affected, a marked change has been made in the combined surface area of the particles. The surface area of the single sphere is 3.1416 square inches, but the combined surface area of the one million spheres is 314.16 square inches. In other words, a mass of small particles, occupying the same space as one or more large particles, has a much greater total surface area.

167. Internal Surface Area of the Soil Mass.—The internal surface area is the combined surface area of the individual particles in a mass. The smaller the particles, the greater the internal surface area of a unit mass. In a mass of particles uniform in

shape but varying in size, the internal surface area may be calculated by separating the particles into their various sizes, measuring the average size, calculating the surface area of each size, multiplying by the number of individuals, and adding the totals. In the case of the soil mass the result is of necessity approximate.

The approximate internal surface area of sands, loams, and clays is given by Lyon and Buckman (page 97) as follows:

	Square Inch per Gram	Square Foot per Pound	Acres per Acre-Foot of 3,500,000 Pounds
Sands	89	280	22,549
Loams	294	926	74,410
Clays	653	2057	165,270

168. Soil Volume.—The weight of any substance may be determined by multiplying its specific gravity by its volume. As the soil is not a solid mass, the weight of a unit, *i.e.* a cubic foot, is less than might be assumed from its real specific gravity. (The specific gravity is determined by the specific gravity bottle, picnometer, and represents an absolute solid soil or 100 per cent soil material.) As a consequence, the dry weight of a block of soil, of which the volume *in situ* is known, divided by the weight of the same volume of water, is called the "apparent specific gravity," or better, the volume weight.

The determination of specific gravity is of little value due to the extremely small differences in the mineral portion of the soil. Smith[1] has shown that the specific gravity of a mineral soil, regardless of the size of the particle, varies between the narrow limits of 2.6 and 2.7. If, however, organic matter is present, the specific gravity will be reduced; muck soils for instance, may have a specific gravity as low as 1.5.

169. The Volume Weight of Soils.—The volume weight or the apparent specific gravity of the soil mass represents the soil material that is actually present. As the larger particles tend to lie in closer contact than the smaller, the weight of a given volume of the former is usually greater than that of the latter; thus sands have a volume weight of 1.55 to 1.70, while clays have a volume weight of 1.10 to 1.35. The volume weight may

[1] Smith, Alfred, "Relation of the Mechanical Analysis to the Moisture Equivalent of Soils," *Soil Science, 14*, pp. 471-476. 1917.

be varied by tillage, addition of organic matter, etc. It may be determined either in the laboratory or the field. A majority of the methods for its determination have been described by Israelsen.[2]

170. Weight of Soil.—The weight of a soil may be determined by multiplying the volume weight of one cubic foot by the volume weight of one cubic foot of water, 62.42 pounds. The weight of a dry soil varies according to the size and arrangement of the particles and the organic matter content. Muck soils weigh as little as 25 pounds per cubic foot, silts and clays 60 to 80, and sands 100 to 110. This weight may be easily converted to acre inches. (An acre inch of water weighs 226,000 pounds.) The weight of an acre of loam soil to a depth of 6 2/3 inches is assumed to be 2,000,000 pounds.

171. Pore Space.—That part of the soil mass not occupied by the particle is called pore space, that is, porosity of the mass. This space is occupied by the liquid and gaseous phases of the mass. It is affected by all the factors affecting the volume weight. It may be more or less accurately calculated from the specific gravity and volume weight data as follows:

$$\text{Per cent of pore space} = 100 - \left(\frac{\text{volume weight}}{\text{specific gravity}} \times \frac{100}{1}\right).$$

The amount of pore space in a soil is very important from the standpoint of crop production. It varies widely according to the class of soil. Due to the fact that they resist compaction, the finer classes usually have a greater pore space than the coarser classes (Fig. 14); for instance, clays have a pore space of approximately 50 per cent, while sands may be as low as 30 per cent. In this space all the phenomena related to the life-giving properties of the soil take place. It is also the space partially occupied by plant roots; consequently this space must, conscientiously or unconscientiously, be considered in all soil manipulations.

172. Effect of Organic Matter on Physical Properties.—The natural or artificial introduction of organic matter into the soil mass exerts a mechanical effect of forcing and holding apart (for various lengths of time) the soil particles and aggregates. The soil mass tends to form a cast or casing about the organic

[2] Israelsen, O. W., "Studies on Capacities of Soil for Irrigation Water," and "A New Method for Determining Volume Weight," *Jour. Agr. Resch.*, *13*, pp. 1-36. 1918.

matter. When the organic matter decomposes, this casing has a tendency to retain its original form. In the case of heavy soils, the channels formed may remain for varying lengths of time. This action results in increased permeability and greater freedom for air and water movement. Under humid conditions, and in the heavier soil types, the results are usually beneficial as

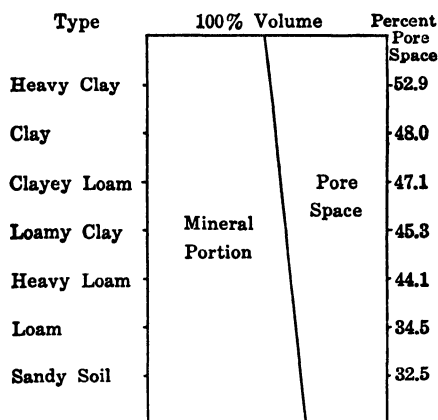



Fig. 14.—Percentage of pore space in soils of different texture. (Adapted from Lyon and Buckman.)

micro-biological activities are stimulated. Under deficient moisture conditions or in light soils an excessive amount of organic matter may so stimulate aeration as to produce a drying-out effect.

When organic matter is distributed through the soil mass and decomposes, it tends to form a coating over the mineral particles. This coating has the effect of darkening the color of the mass, thus influencing the temperature relationships. The colloidal condition (104) of organic matter enables it to have a more or less marked effect on soil moisture. Keen [3] shows that the addition of 14 tons of manure per acre annually has, at Rothamsted, increased the moisture-holding power of the soil 5 per cent. Measurements of the moisture content at different vapor pressures showed a higher equilibrium moisture content for high organic matter soils.

Studies of the influence of organic matter on the water-holding

[3] Keen, B. A., "Some Physical and Physico-chemical Effects of Soil Organic Matter," *Jour. Amer. Soc. Agron.*, *19*, pp. 362-368. 1927.

capacity of Hempstead silt loam in Minnesota[4] showed little influence from the standpoint of productivity. A comparison was made, over a twenty-year period, of the moisture relations of two adjacent plots. Plot 3 was rotated to corn, barley, oats, and clover, and had received a total application of 25 tons of manure. Plot 4 had grown corn for 22 successive crops without manure. The average organic matter (organic carbon $\times$ 1.724) of a 12-inch sample in Plot 3 was 4.76 per cent and in Plot 4, 3.39 per cent. When the season was wet, and a cool higher moisture content prevailed in the surface foot of soil, crop growth in Plot 3 was apparently stimulated, but when the season was drier and warmer much smaller differences were found.

173. Effect of Wetting.—If water is added to a dry soil in an amount sufficient to produce maximum plasticity, it replaces all the air in the interspaces and completely envelopes all the particles If the particles are of large size (sands) there is no change in the state of the mass. If, however, the particles are very small (clays, etc.) or the soil mass is a mixture of varying sized particles, there may be a change of state, that is, the mass may swell. The action may be attributed to the colloidal content of the mass which when moistened forms a gel.[5] When the maximum degree of plasticity is obtained, the gel is in equilibrium and distributed equally throughout the mass. As the gel imbibes water it swells, but the volume of the gel plus the volume of the water added is less than the original volume of the two components. In other words, the water is compressed or forms a part of the gel. The swelling of soil appears to be a result not only of its colloidal content but of its organic matter content as well. Different soils show marked differences in the rate of swelling, and chemical treatments modify this rate. There is apparently a correlation between the swelling constant, the mechanical composition, the moisture equivalent and hygroscopic moisture content, although there seems to be no fixed ratio.[6]

[4] Alway, F. J., and Neller, J. R., "A Field Study of the Influence of Organic Matter upon the Water-Holding Capacity of a Silt-Loam Soil," *Jour. Agric. Res.*, *16*, pp. 263-278. 1919.

[5] Tempany, H. A., "The Shrinkage of Soils," *Jour. Agric. Sci.*, *8*, pp. 312-332. 1917.

[6] Vinson, A. E., and Catlin, C. N., "Determination of the Swelling Coefficient of Dry Soils When Wetted," *Jour. Amer. Soc. Agron.*, *14*, pp. 302-307. 1922.

Haines, W. B., "The Volume Changes Associated with Variations of Water Content in Soils," *Jour. Agric. Sci.*, *13*, pp. 298-310. 1923.

The amount of swelling appears to be variable. Hilgard [7] states that clay soils may be several inches higher when wet than when dry. Wollny [8] found loams would swell as much as 22 per cent, while peats would swell 46 to 84 per cent.

All fine-textured soils do not behave physically in the same way.[9] One type of clay moves little or none with wetting and drying, another swells and shrinks greatly. The latter type, which is most difficult to cultivate, is of the plastic group of soils which are so impervious in the extreme cases as to have very poor drainage and aeration.

174. The Effect of Drying.—When soil dries it tends to shrink (contract). The shrinkage of soil due to the progressive loss of moisture may be distinguished in two well-defined stages.[10] First, the concentration of water is adjusted throughout the mass, moving from the interior to the exterior as it is evaporated from the surface. The contraction in volume in this stage is proportional to the amount of water loss. Second, a point is reached where the internal friction, due to the approach of the particles, exerts a retarding effect on the rate of contraction. The mass may be still permeated with water, but there is a deviation from the straight line of water loss. In other words, there is a state of tension in the mass due to the pull of evaporation and resistance to pull by the particles. When the tension of the gel condition in the mass is overcome by the resistance of the particles to the pull, air bubbles appear in the interstices and the continuity of the gel skeleton is ruptured. The shrinkage is apparently due to the degree of dispersion of the particle, which determines the soil moisture content at the point of maximum plasticity, and the degree of aggregation of the particle into compound grains. The greater the gel (colloidal) condition and the less the aggregation, the greater the contraction in volume on drying.

175. Soil Cracking.—Even after shrinkage has ceased, the soil mass continues to lose moisture. If the soil contains an

[7] Hilgard, *Soils*, p. 141. 1906 ed.

[8] Wollny, E., *Die Zersetzung der Organischen Stoffe*, p. 237. Heidelberg, 1897.

[9] Bennett, H. H., "Some Comparisons of the Properties of Humid, Tropical, and Humid-Temperate American Soils, with Special Reference to Indicated Relations between Chemical Composition and Physical Properties," *Soil Science*, *21*, pp. 349-375. 1926.

[10] Tempany, H. A., "The Shrinkage of Soils," *West Indian Bul.*, *17*. pp. 107-118 (1917); Mason, T. G., "The Ecological Significance of Soil Shrinkage," *West Indian Bul.*, *19*, pp. 125-137. 1922.

appreciable amount of colloidal material, a point is reached where the gel skeleton is ruptured before the moisture content is exhausted. When this point is reached, the gel structure breaks at the weakest point and the local areas continue to contract. Under field conditions, this results in the surface of the area cracking irregularly. These cracks quickly deepen often to great depths, exposing and breaking crop roots.

176. The Effect of Freezing.—When water freezes it has a tendency to form ice crystals in the larger capillary spaces. These crystals grow at the expense of the water in the smaller capillaries, thus producing a drying effect that may result in a granulation or flocculation [11] of the smaller soil particles. The freezing process causes the soil particles to be pushed apart, but not to such an extent as to prevent their maintaining contact at many points, where, owing to the increased density of the colloidal coatings, they remain firmly bound together. At the points where the ice crystals form, the cohesion may be completely broken, thus leaving a structure of soil crumbs separated from each other by layers of ice. The final result will depend on the kind of weather following. If the soil continues frozen there may occur considerable evaporation and drying. If this is followed by a gradual rise in temperature further drying may be facilitated by the ease with which the excess water may drain out of the extended capillaries. As the air enters and dries out the soil crumb, they tend to retain the loose friable soil structure.

On the other hand, alternate freezing and thawing tends to break down rather than increase the crumb structure. The changes are too rapid to allow the necessary slow drying effect. As a result the soil tends to become somewhat puddled. This puddling effect has a marked influence on plants, as the swelling of the ice crystals may actually lift the plant a small amount each time a freeze takes place. If there is a sufficient number of freezes and thaws, the well-known heaving effect may be observed.

177. Soil Crusting.—The surface of the soil normally contains a sufficient concentration of salts to keep the crumb-forming soil colloids in a gel condition. The puddling effect of freezing or the action of rain water in replacing the moisture film of the

[11] Ehrenberg, P., *Die Boden Kolloide*, p. 142. 1st ed. T. Steinkopff. Leipzig, 1915.

surface layers tends to soften and dissolve this condition. Falling raindrops by impact may now completely destroy the crumb structure and produce a puddled condition at the surface, which on drying out results in the formation of a crust. Thus crusting is favored by a fine-textured soil or one having a finely pulverized surface. The effect of the crust is to retard or prevent seed germination and to favor rapid evaporation.

CHAPTER 14

PHYSICAL PROPERTIES AND PLANT GROWTH

The foregoing pages indicate that from the physical standpoint alone the soil cannot be considered as a static (unchangeable) medium. It is dynamic (changeable) in nearly every phase. This fact is amply demonstrated in the temperature, air, and water changes constantly taking place. Each of these has a bearing on plant growth. Rarely do we find a condition where one factor predominates throughout the period of plant growth to the exclusion of all others. Usually plant growth is a result of many physical soil factors, some of which are more active at certain stages than are others.[1]

178. The Soil Mass.—The soil mass is not an admixture of individual particles, each independent of the other. Keen [2] views it as a system of mineral particles of all sizes, which are covered with a colloidal film, and that this film is relatively thicker the smaller the particle. Bouyoucos [3] shows that the colloids do not exist entirely as a coating around the soil grain, but also as independent components either pure or containing different amounts of impurities and scattered irregularly throughout the soil mass. Comber [4] believes that these particles are aggregated to form compound particles. These aggregates are conceived as having a large nuclei surrounded by particles which become

[1] For a general discussion of the relation of Soil Physics to plant growth see:

Free, E. E., "Studies in Soil Physics," *Plant World*, V, 14. 1911. (1) "The Physical Condition of Soils," pp. 29-39; (2) "The Movements of Soil Water," pp. 59-66; (3) "Soil Water and the Plant," pp. 110-119; (4) "The Physical Constant of Soils," pp. 164-176; (5) "Soil Temperature," pp. 186-190.

For a general discussion of the biological significance of the physical and chemical properties of matter see Henderson, L. J., *The Fitness of the Environment*. The Macmillan Co., New York, 1913. 317 pp.

[2] Keen, B. A., "The Relations Existing between the Soil and Its Water," *Jour. Agric. Sci.*, *10*, pp. 44-71. 1920.

[3] Bouyoucos, G. J., "Do Colloids Exist as a Coating around the Soil Grains? *Soil Sci.*, *21*, pp. 481-487. 1926.

[4] Comber, N. M., "The Flocculation of Soils," *Jour. Agric. Sci.*, *10*, pp. 425-430. 1920.

smaller and smaller, from the center of the aggregate outward. The clay or smaller particles ultimately impose their emulsoid nature on the whole aggregate. The extent of this aggregation has a marked effect on the structure of the soil as a whole; for instance, the crumb is generally regarded [5] as meaning a relatively large loose aggregate.

179. The Physical State and Plant Growth.—From the standpoint of plant growth we may view the soil mass as existing in two states, one primarily mobile, the other primarily immobile. The primarily mobile state is represented mainly by the gaseous and aqueous phases. These phases are constantly undergoing more or less rapid change. The primarily immobile state is represented by the solid portion. This portion is also changing, but the rate is rather slow and there is no great fluctuation as in the other states.

Plant growth is dependent upon the proper equilibrium or balance existing between the three phases, solid, liquid, and gaseous. Information on the relative importance of each of these on plant growth is lacking. This is due primarily to the fact that their functions are so closely connected. For instance, the immobile portion of the soil has a number of functions in relation to plant growth. First, it may be looked upon as the skeleton or framework (8) of the soil mass on which all functions take place. This skeleton not only supports the soil functions but it acts as a mechanical support for plants. Second, the skeleton is not an inert material; rather it gives up to, and takes from, the mobile states many of its constituents. These constituents may be and usually are the raw materials for the support of the life-giving properties of the soil. Therefore the skeleton acts as a storehouse for the soil-derived food of plants, but the conditioning of this food and rendering it acceptable to the plant is dependent upon the proper equilibrium of all three phases. Third, the skeleton acts as an agent in continually changing the various states. It swells, shrinks, and passes through many physical changes that accelerate or retard the activities of the mobile state. In other words, it acts similarly to the muscles and tendons of the animals (8). On the other hand, the mobile portion may and usually does act as a carrier of the soil-derived food from the skeleton to the plant, or as a regulator of the life-giving

[5] Hilgard, E. W., *Soils*, p. 109, 1918 ed.

processes of the soil. These functions are not carried out individually; they are dependent on the condition of the skeleton.

One must keep in mind also that the relationships existing between the various soil states are not the same throughout the area occupied by plant roots. The roots extend to varying depths, and the condition of the various depths may vary widely. Hence we find that the physical state of the various depths or horizons (55) is very important.

180. Soil Conditions and Root Development.—Plants have different types of roots and different habits of feeding in the soil. The plant may be deep or shallow-rooted and feed either at the surface or at varying depths. In general, the root development of the plant is governed by the condition of the soil, and the deeper the feeding habit the more important the characteristics of the soil profile. For instance, the growing plant is constantly extending its root system. As a root elongates, the older portions tend to become cuticularized and lose their power of feeding. The feeding powers of the plant are located mainly in the newer portions of the roots. These are constantly changing in position. As the change of position is governed by the soil characteristics, then the ability of the plant to feed from a soil is governed by these same factors. This point may be illustrated by a study of Fig. 15, showing the extension of roots by the wheat plant at different stages of growth.

FIG. 15.—Area of soil occupied by wheat roots at different stages of growth. (Adapted from Weaver.)

181. Soil Temperature and Plant Growth.—The environmental factor of soil temperature is a controlling one in the germination and growth of all seed plants. If the temperature is too low or too high, seeds will not germinate. It follows, therefore, that between these two extremes there is an optimum point at which best germination is secured, as shown by Table 23, adapted from Warrington, page 140.

TABLE 23

MINIMUM, OPTIMUM, AND MAXIMUM TEMPERATURE FOR GERMINATION IN DEGREES FAHRENHEIT [6]

SEED	MINIMUM	OPTIMUM	MAXIMUM
Barley, vetches, peas, rye, wheat, oats	32–40	61–77	88–100
Turnip, red clover, buckwheat	32–40	77–88	88–111
Corn, sorghum	40–51	88–100	111–122
Tobacco	51–60	77	88–100
Cucumber, melon, pumpkin	60–65	88–100	111–122

Bates and Zon [7] show that the effect of soil temperatures on plants is more concerned with initiation of growth, habit extension, and plant succession, than with rates of growth. They cite as an illustration the temperature of the seed-bed in direct effect on rate and amount of germination; the optimum temperature of the soil in stimulating osmosis; the minimum temperature at which the soil water is sufficiently available to supply transpiration, the temperature at which the soil freezes and cuts off the water supply to plants, the maximum temperature of the soil or soil surface which may be tolerated without injury by the seedling or plant, the influence of air temperature and light upon soil temperature, and the correlation between soil temperature and extremes of drought in the surface soil. It must not be concluded, however, that soil temperature is chiefly concerned with the growth of higher plants. All biological activities are influenced to the same degree, consequently the complex functions of micro-organisms attain their maximum activities at an optimum temperature.

182. Air Temperature and Vegetation.—Plants require a certain temperature condition (see Table 23) for their growth. During the germination stage this temperature condition is controlled entirely by the soil, but during the growing period it is controlled entirely by the atmosphere. It is controlled, not by the average atmospheric temperature, but by the maximum or minimum temperatures that may persist for only a brief period. Of these two extremes the minimum is by far the more important,

[6] Warrington, R., *Physical Properties of Soils*. Oxford, 1900. 231 pp. See also Camp, A. F., and Walker, M. N., "Soil Temperature Studies with Cotton," *Florida Agric. Expt. Stn. Bul. 189*, 1927.

[7] Bates, C. G., and Zon, R., "Research Methods in the Study of Forest Environment," *U. S. Dept. of Agric. Bul. 1509*, pp. 27-28. 1922. 208 pp.

due to the fact that a condition of killing frost may be produced. Thus the United States may be divided (Chart 1, page 338) into areas based on the length of the growing season.

183. Classification of Temperature in Relation to Plant Life.—Based on temperature requirements, the geographical distribution of different plants, where the moisture is sufficient, may be grouped broadly in latitudinal zones around the world, the several belts in which individual crops dominate being susceptible of more or less definite delineation on a quantitative temperature basis. Two significant values of daily mean temperature for agriculture may be mentioned, those of 50° and 68° F., and the duration of these for one, four, and twelve months, have been made a basis of certain classifications. The polar limit of trees and the more hardy food crops is fairly well outlined by the isotherm of 50° F. for the warmest months of the year. Near this line are found the last groups of trees in the tundras. A temperature of 50° F. for four months closely coincides with the polar limit of the oak and of wheat cultivation.

In general the following classification of temperature in relation to plant life may be made:

1. Tropical belt, with all months warm; that is, the temperature averaging over 68° F.
2. Subtropical belt, with 4 to 11 months warm, averaging over 68° F.
3. Temperate belt, with 4 to 12 months of moderate temperature 50° to 68° F.
4. Cold belt, with 1 to 4 months temperate and the rest cold, below 50° F.
5. Polar belt, with all months averaging below 50° F.

184. Relation of Atmospheric Temperature to Soil Temperature.—The relation of atmospheric temperatures to soil temperature is shown in Fig. 11. It will be noticed that there are two distinct relationships. When the soil is not frozen and there is an opportunity for air movement, the temperature of the soil follows somewhat roughly the temperature of the air. But, when the soil is frozen and little opportunity is offered for free air movement in the pore space, the temperature of the soil tends to remain somewhat constant.

185. Water in Relation to Plant Growth.—A certain amount of water is required by all living bodies for their life processes.

A comparatively insignificant amount is retained by the body, while the majority is used as a regulator of lifė processes. Practically nothing is known of the water requirements of the smaller plants and animals, while a great deal of attention has been paid to the requirements of the economic crop plants. The plant, however, is partially submerged in the soil and partially above it, yet deriving all of its water from the soil itself. As a result, the relation of water to plant growth is not strictly a soil relationship, but a combined relationship of soil and atmospheric conditions and plant characteristics. The factors influencing the water relationship of (transpiration)[8] plants are grouped as follows:

Group A

Atmospheric (Climatic)

1. Temperature
2. Relative humidity
3. Wind velocity
4. Light
5. Radiant heat (radiation)
6. Composition of air
7. Air pressure
8. Evaporation rate of free water
9. Distribution of precipitation, etc.

Group B

Soil

1. Composition
2. Crop-producing power
3. Available moisture content
4. Soil texture
5. Soil structure
6. Topography
7. Exposure
8. Cover
9. Color

Group C

Plant Characteristics

1. Root development
2. Leaf area
3. Leaf arrangement
4. Structure (especially of leaves)
5. Dry weight, as a resultant factor
6. Density of cell sap
7. Relative ability to withstand drought
8. Heat generated within plant as a result of chemical activity
9. Age of plant
10. Moisture content of leaf
11. Cooling effect exerted upon plant itself by transpiration
12. Vital element in the plant affecting its condition
13. Disease

I. The Climatic Factor.—Climatic changes have a marked influence on transpiration. A low annual rainfall in a region with a cool, humid "wind-still" climate may produce as good or better crop response as a much larger rainfall in a region where the air, at least during the growing season, is dry, hot, and windy.

[8] Kiesselbach, T. A., "Transpiration as a Factor in Crop Production," *Nebraska A. E. S. Resch. Bul. 6*. p. 39. 1916. 214 pp.

This effect is due, in the first case, primarily to a lower value of the climatic water-dissipating influences. Thus climatic factors affecting the evaporation from a free water surface (evaporation) also affect plant transpiration and in areas where this rate is high may prove a serious handicap in crop production. In some sections, particularly in the Great Plains area, the evaporation rate is subject to great temporary acceleration from strong, hot winds. A few hours of hot winds, coming as they are apt to do in periods of drought, seem to be more fatal to crops, particularly corn, than are as many days of drought minus the hot winds.

II. The Soil Factor.—The soil factor is equally as important as the climatic factor, due to the fact that the characteristics and growth rate of the plant are dependent upon the soil conditions noted above. Soils of equal moisture content of the same type, and under similar climatic conditions, may have different crop-producing powers. The higher the crop-producing power of the soil, the more efficient becomes the plant in water utilization. This does not mean that less water is required by the plant (in fact, the consumption per plant or per acre is actually greater) but that a smaller amount of water is required to produce a unit of dry matter (**186**). For example, the crop-producing power of a soil may be increased by the application of manure, etc. If this is done, the amount of water required, per unit of dry matter produced, is reduced, but the total dry matter produced is increased, thus increasing the amount of water utilized. In other words, the ratio of water loss to dry weight is lower because the plants grow in a more normal manner. Thus the soil factor is one concerned primarily with plant nutrition and not with transpiration. The latter is a result of the nutritional condition.

III. The Plant Characteristics.—It is well known that some plants are especially adapted to dry and others to humid conditions. For instance, the grain sorghums are well suited for dry farming conditions, while corn and cotton are better suited for humid conditions. The ecological distribution of native plants is controlled mainly by moisture and temperature. Physiological studies are showing that the plant characteristics play an important part. For instance, it has been shown that desert plants[9]

[9] Fitting, Hans, "Die Wasserversorgung und die Osmotichen Druckverhaltnisse der Wustenpflanzen," *Ztschr. fur Bot.* 3, pp. 209-275. 1911.

possess a high osmotic pressure and are able as a consequence to extract moisture from a comparatively dry soil in which the water films are very thin. The relation of water to plant growth is in many cases one of root development,[10] the shallow-rooted plants being influenced by the air-water balance **(118)** in the upper soil horizon (A and B), while the tap-rooted plants may penetrate to the deeper levels (C horizon).

186. Water Requirement of Plants.[11]—As has been indicated, the water requirement (the units of water required to produce a unit of dry plant product) of plants is a variable factor. This point has been the subject of extensive investigation. A summary of the average water requirement of plants grown at Akron, Colorado,[12] in 1911, 1912, and 1913 is shown in Table 24.

TABLE 24

POUNDS WATER REQUIRED TO PRODUCE ONE POUND DRY MATTER

(Mean of Genus)

Grain Crops

Barley	534	Flax	905	Proso	293	Sorghum	322
Buckwheat	578	Millet	310	Rice	710	Teosinte	383
Corn	368	Oats	597	Rye	685	Wheat	513

Legume Crops

Alfalfa	831	Clover, red	797	Pea, Canada, field	788
Bean, soy	744	" sweet	770	Vetch, hairy	690
" navy	682	Cowpea	571	" purple	935
" horse	776				

Other Crops

Beet, sugar	397	Potato	636	Squash	748
Cantaloupe	667	Pumpkin	834	Turnip	639
Cabbage	539	Rape	743	Watermelon	600
Cotton	646				

Native Plants

Cockle-burr	432	Lambs quarter	801	Sunflower	683
Grass, buffalo and grama	389	Pigweed	297	Wheat-grass	1076
Gumweed	608	Purslane	292		
		Ragweed	948		

[10] Weaver, J. E., *Root Development of Field Crops.* McGraw-Hill Book Co., New York, 1926. 291 pp.

[11] For a summary and list of investigators see p. 36, *Nebraska Research Bul. 6.* 1916. See also *U. S. Dept. of Agric. Bur. Plant Ind. Bul. 285.* 1913.

[12] Briggs, L. J., and Shantz, H. L., "Relative Water Requirement of Plants," *Jour. Agric. Resch. 3*, pp. 1-63. 1914.

The seasonal (climatic) effect on the water requirement of plants under field conditions is shown in Table 25. In this case no attempt was made to control conditions; for instance, the difference in water content of the soil at seeding and harvest is figured as the water used from the soil, and the amount of rain falling in the interval is charged to the crop. (This is not scientifically accurate, as some of this water is lost by evaporation.) The table is, however, of practical value in showing that an inch of water in a favorable season will go much further than a like amount in an unfavorable one, hence causing a marked variation in the amount required to produce one pound of dry matter.

TABLE 25

SEASONAL VARIATION IN WATER REQUIREMENT OF WHEAT AND CORN [13]

Crop	Year	Average per Cent Water in Upper 6 Feet of Soil		Per Cent Water Used from Soil	Water Used from Soil. Tons per Acre	Precipitation during Growing Season. Inches	Total Water Available to Crop from Soil and Precipitation Tons per Acre	Dry Matter Produced. Pounds per Acre	Pounds Water Required for One Pound Dry Matter
		Seeding	Harvest						
Spring wheat	1908	11.8	11.3	0.5	52.2	12 8	1505.3	3980	756
	1909	13.6	13.1	0.5	52 2	12.1	1422.5	3530	806
	1910	12.6	10.5	2.1	219.5	6.2	926.3	1350	1372
	1912	16.9	8.5	8.4	878.2	7.6	1740.0	2580	1345
Corn	1908	13.0	8.6	4.4	460.0	14.4	2090.8	4380	955
	1909	11.7	12.8	0 9	....	14.2	1516.4	5000	606
	1910	13.9	11.1	2.8	262.7	5.4	898.6	2950	610
	1912	16.8	12.3	4.5	470.4	6.8	1240.6	5120	485

187. Relation of Plant to Soil Water.—It has been shown that in the air-water balance, the water may occupy from approximately 0 to 100 per cent of the pore space. A plant cannot grow in soils containing too little [14] or too much water, consequently, there is some point between these two extremes that is optimum for the plant. This point is diagrammatically shown in Fig. 16.

The total amount of water in the soil gives no indication of its crop-producing powers. It is the amount that a soil will retain,

[13] Burr, W. W., "The Storage and Use of Soil Moisture," *Nebr. Res. Bul. 5*, 1914, p. 78.

[14] Briggs, L. J., and Shantz, H. L., "The Wilting Coefficient for Different Plants and Its Indirect Determination," *U. S. Dept. of Agric. Bur. Plant Ind. Bul. 230.* 1912. 72 pp.

The wilting coefficient is usually determined by means of the plant, but

capillary and hygroscopic, rather than its total water-holding capacity that influences plant growth, for the reason that plants use little or none of the free gravitational water.

FIG. 16.—Plant-soil water relationships.

The plant root needs both air and water in order to develop. Too much water is injurious because of a lack of air, also too little water is injurious and the plants wilt. The rootlets remove the water surrounding them, thus cutting down the amount, and if the soil is unable by capillarity to move the water rapidly enough, wilting results. In other words, there is a maximum point of exhaustion of water from the soil by the plant and this point is that at which the force exerted by the plant in obtaining water is equaled by the attraction of the soil for the water. This point varies for different plants and for different soils,[15] the variation being ascribed to

may also be found indirectly from other soil constants to which it bears a more or less definite relation. For instance,

$$\text{wilting coefficient} = \frac{\text{moisture equivalent}}{1.84} \text{ or } \frac{\text{hygroscopic coefficient}}{0.68} \text{ or } \frac{\text{moisture holding capacity}}{2.90}.$$

The permanent wilting of the plant, however, has been shown to be a function of atmospheric evaporation.

See Caldwell, J. S., "The Relation of Environmental Conditions to the Phenomena of Permanent Wilting of Plants," *Physiol. Res.*, *1*, pp. 1-56. 1913.

Shive, J. W., and Livingston, B. E., "The Relation of Atmospheric Evaporating Power to Soil Moisture Content at Permanent Wilting in Plants," *Plant World*, *17*, pp. 81-121. 1914.

[15] The importance of the colloidal content of the soil is indicated here, some plants wilt and die in some clay soils which may contain as much as 20 per cent of water, while in the case of some sands practically devoid of colloids, the plants reduce the moisture content to less than 1 per cent before they begin to wilt and die.

differences in root extension, in ability to adjust itself to a slow intake of water and in the osmotic pull exerted by the plant. At the minimum point of exhaustion the plant can obtain no more water, and will suffer until water is supplied. This point is in direct correlation with the maximum water-holding capacity of the soil. A fine soil having a high water-holding capacity will exert a strong resistance to the use of water by the plant, while a sandy soil with a lower maximum, has a correspondingly lower minimum of water which is not available. Some water may be taken from the soil below the minimum point, but not in sufficient amount or rapidly enough to promote growth or even to sustain life for any considerable period.

188. Movement of Water in Relation to Crop Production.— The utilization of water by plants is not regular, that is, the utilization does not always increase regularly with increase in plant growth. There are certain periods when the plant may demand an increased amount of water from the soil.[16] For the grain crops this period coincides with the time of heading out and blooming; on the other hand, plants like potatoes utilize the soil moisture with greater regularity.

In order to replace the water utilized by plants the soil must first be capable of retaining the water gained from rainfall, and second, must be able to move it to the plant in sufficient amount to support plant growth. The effect of soil type on the penetration and retention of water therefore becomes very important. For instance, Stewart,[17] in a series of experiments designed to bring out the effect of moisture, shows that a 0.58 inch precipitation penetrated 12 to 18 inches in a medium sand, and only 6 inches in loam in a 24-hour period. However, after eight days the effect in the sand had disappeared but was evident at 18 to 30 inches in the loam.

The effect of percolation and evaporation is shown by Fraps,[18] who found that percolation is affected to a considerable extent by the relative moistness of the soil, by the type, the climatic, the

[16] Tulaikov, N. M., "The Utilization of Water by Plants under Field and Greenhouse Conditions," *Soil Science, 21*, pp. 75-91. 1926.

[17] Stewart, H. W., "A Study of Some of the Factors Affecting the Supply of Moisture to Crops in Sandy Soils," *Soil Science, 21*, pp. 197-217. 1926.

[18] Fraps, G. S., "Moisture Relation of Texas Soils," *Jr. Am. Soc. Agron.*, 7, pp. 31-33. 1914. *Texas Agric. Expt. Sta. Bul. 171.* (1914); "Moisture Relations of Some Texas Soils," *Texas Agric. Expt. Sta. Bul. 183.* 1915.

treatment, and the rainfall. A tilled soil held more water than an untilled, applications of manure increased the water-holding capacity, evaporation was greater from sandy than from heavier soils, while percolation was greater from the heavier types.

In general, it appears that the movement of water in the soil by capillarity is too slow to support plant growth. The supply for plant use seems to be dependent upon precipitation or irrigation, the initial amount in the soil, the foraging ability of the plant for water, and the willingness of the soil to share with the plant.

PART III

THE CHEMICAL PROPERTIES AND FUNCTIONS OF SOILS

The chemical phenomena of the soil may be regarded from two viewpoints which may be expressed as follows: First, the "geochemical" concept—the properties and functions of the mineral or solid portion of the soil mass. This concept deals primarily with the form and composition of rock masses. The soil is a secondary consideration. It is usually regarded as a transitional phase between the breaking down of the rock masses and the formation of other masses.

The second viewpoint is usually implied but not defined. It may be called the "nutritive-chemical" concept. This concept deals primarily with the properties and functions of the soil mass that influence soil productivity and soil fertility.

The first viewpoint is mainly that of the geölogist, the second is that of the edaphologist.

CHAPTER 15

SOIL COMPOSITION

The soil mass is made up mainly of materials found in the earth's crust to which have been added varying amounts of organic matter. Its formation has resulted in a complex mixture of dynamic materials.

189. Elements of the Earth's Crust.—The earth's crust consists of a more or less intimate mixture of elements that are in various degrees of abundance. The amount and character of these elements and their distribution have a marked influence upon the character of the original rock formation, hence may have a marked influence on the soil derived from these rocks or on the ability of that soil to support plant growth. The following table shows the relative abundance of the chief elements of the earth's crust. The elements marked × are in scarcely detectable amounts.

TABLE 26

THE CHIEF ELEMENTS IN THE EARTH'S CRUST IN ORDER OF THEIR ABUNDANCE[1]

Element		Element		Element	
1. Oxygen	46.43	16. Barium	0.048	31. Arsenic	×
2. Silicon	27.77	17. Chromium	0.037	32. Cadmium	×
3. Aluminum	8.14	18. Zirconium	0.028	33. Tin	×
4. Iron	5.12	19. Carbon	0.027	34. Mercury	×
5. Calcium	3.63	20. Vanadium	0.021	35. Antimony	×
6. Sodium	2.85	21. Nickel	0.019	36. Molybdenum	×
7. Potassium	2.60	22. Strontium	0.018	37. Silver	×
8. Magnesium	2.09	23. Lithium	0.003	38. Tungsten	×
9. Titanium	0.629	24. Copper	0.002	39. Bismuth	×
10. Phosphorus	0.130	25. Cerium, etc.	0.001	40. Selenium	×
11. Hydrogen	0.127	26. Glucinum	×	41. Gold	×
12. Manganese	0.096	27. Cobalt	×	42. Bromine	×
13. Fluorine	0.077	28. Boron	×	43. Tellurium	×
14. Chlorine	0.055	29. Zinc	×	44. Platinum	×
15. Sulphur	0.052	30. Lead	×		

It is important to note that only eight of these elements are in an amount exceeding one per cent and that these eight consti-

[1] Washington, H. S., "The Chemistry of the Earth's Crust," *Annual Report, Smithsonian Institution*, pp. 269-318. 1920.

tute 98.63 per cent of the entire crust. Further, the first twelve elements constitute 99.61 per cent of the crust, thus leaving only 0.39 per cent for all the other elements, some of which are absolutely necessary for plant growth. It should be noted also that the most abundant elements are, on the whole, those of low atomic weight, while the rarer ones are those of high atomic weight. The latter are generally spoken of as metals and usually occur in extremely localized areas.

190. The Metallic Elements.—The elements of high atomic weight are of exceedingly great importance in spite of their rare occurrence in the crust of the earth. They are distinct from the elements forming materials from which soils are derived, in their chemical combinations and in their present state. We find many of them occurring in nature in the uncombined state; for instance, copper, silver, gold, mercury, zinc, arsenic, antimony, sulphur, selenium, tellurium, and the metals of the platinum group. These elements do not form oxides and only rarely do they form silicates, except in the case of copper and zinc. It is supposed that such existing combinations of these elements as the oxides, chlorides, sulphides, arsenides, selenides, etc., are of secondary rather than primary formation. These elements are of great importance from the standpoint of geology and metallurgy, but, with the single exception of sulphur, have little importance from the standpoint of soils and plant growth. They are termed the ore elements and have been grouped into a great class designated by the term "metallogenic elements."

191. The Petrogenic Elements.—The elements of low atomic weight constitute the greater portion of the earth's crust. As these elements are destined to form the great rock masses of the present crust of the earth, the term petrogenic has been applied to them. These elements form more complex combinations than the metallogenic group. The combinations are made primarly among themselves, but some with the metallogenic group. The system of formation appears to be so very complex that it is practically impossible to trace out any basis foı a law to govern it. The reactions apparently were strivings toward a chemical equilibrium and a maximum of stability was the ultimate result. In the end, the petrogenic elements, with their several combinations, became more or less intimately mixed with the metallogenic elements.

The petrogenic elements occur normally as primary minerals forming such salts as oxides, silicates, fluorides, and chlorides, but rarely forming sulphites, selenides, tellurides, arsenides, etc. Thus oxides of silicon, aluminum, magnesium, titanium, iron, manganese, as well as carbonates, fluorides, chlorides, and silicates, of sodium, potassium, ammonium, magnesium, calcium, aluminum, iron, manganese, and cerium may be of more or less common occurrence in rocks.

192. The Mineral Constituents of Rocks.—When the elements form a distinct stoichometric compound, a compound of definite chemical constitution, that compound is spoken of as a mineral. About 1000 minerals are known but only a few are predominant in the formation of rocks. This is especially true of the first kinds of rocks (igneous) formed. These were primarily oxides of silicon and iron; silicates of aluminum, potassium, sodium, calcium, magnesium, iron, and titanium; metasilicates of calcium, magnesium, iron, aluminum, sodium and potassium; alumino-silicates of potassium, iron, and magnesium; and orthosilicates of iron, magnesium, sodium, and aluminum. Some of the combinations are very simple, consisting of one base and one acid radicle, while some are exceedingly complex, consisting of a number of bases and acids. Further, some of the minerals of similar chemical composition have formed distinctly dissimilar rocks. The study of these minerals, their influence on rock formation and the kinds of rocks formed from them, either primarily or secondarily, belongs to the realm of geology. We may confine our attention to those rocks from which soil is commonly formed.

193. Common Soil-Forming Minerals.—The bulk of the soil mass has been derived from a comparatively small number of minerals. A mineralogical analysis, using petrographic methods, was made by Fry [2] (page 9) for the twenty most important soil minerals found in the Great Plains, the Glacial and Loessal, the River Flood Plains, and the Coastal Plains provinces. The minerals sought, their formulas, and their distribution follow:

1. Quartz: SiO_2; found in plentiful amounts in all soil types.
2. Magnetite: Fe_3O_4; found in all soil types but never exceeding a trace.

[2] Robinson, W. O., Steinkoenig, L. A., and Fry, W. H., "Variation in the Chemical Composition of Soils," *U. S. Dept. of Agric. Bul. 551*, 1917. See also Burt, F. A., *Soil Mineralogy*, D. Van Nostrand Co., Inc. New York, 1927. 84 pp.

3. Orthoclase: $KAlSi_3O_8$; found in plentiful amounts in soils from the Great Plains, in small amounts in soils from the Glacial and Loessal province, in very small amounts in the River Flood Plains province, and in traces or not at all in the Coastal Plains province.

4. Microcline: $KAlSi_3O_8$; found in slight amounts in the Great Plains province, traces in the Glacial and Loessal and River Flood Plains provinces, but not in the Coastal Plains province.

5. Biotite: About $(H,K)_2(Mg,Fe)_2Al_2Si_3O_{12}$; found in very small amounts in the Great Plains and Glacial and Loessal provinces, occasionally traces but mostly not at all in the River Flood Plains and Coastal Plains provinces.

6. Muscovite: $H_2K\ Al_3Si_3O_{12}$; traces to very small amounts found in each of the four provinces.

7. Plagioclase: Isomorphous mixtures of $NaAlSi_3O_8$ and $CaAl_2Si_2O_8$. Plentiful to very small amounts in the Great Plains province, traces in the Glacial and Loessal and the River Flood Plains provinces, but rarely found in the Coastal Plains province.

8. Hornblende: Chiefly $Ca(Mg,Fe)_3Si_4O_{12}$ with $Na_2Al_2Si_4O_{12}$ and $(Mg,Fe)_2(Al,Fe)_4Si_2O_{12}$; found in traces to small amounts in the Great Plains and Glacial and Loessal provinces and traces or not at all in the other two provinces.

9. Epidote: $HCa_2(Al,Fe)_3Si_3O_{13}$. Traces to very slight amounts in the first two provinces, occasionally a trace but mostly not at all in the other two provinces.

10. Titanite: $CaTiSiO_5$. Traces in the Glacial and Loessal province, not found in the River Flood Plains, and only an occasional trace in the Great Plains and Coastal Plains provinces.

11. Cyanite: Al_2SiO_5; not found in the first three provinces, and only occasionally a trace in the Coastal Plains province.

12. Sillimanite: Al_2SiO_5; traces in the River Flood Plains province, occasionally a trace in the Coastal Plains, but not found in the Great Plains and Glacial and Loessal provinces.

13. Tourmaline: A complex silicate of Bo and Al with Mg, Fe or the alkali metals prominent. Not found in the Great Plains province, but traces found in the other three provinces.

14. Rutile: TiO_2; found in traces to very small amounts in practically every soil type examined.

15. Zircon: $ZrSiO_4$; traces found in practically every soil examined.

16. Garnet: $\ddot{R}_3\dddot{R}_2(SiO_4)_3$ in which $\ddot{R}$ is Ca, Mg, Fe, and Mn, and $\dddot{R}$ is Al, Fe, and Cr, and rarely Ti; rarely found and then only a trace.

17. Zoisite: $Ca_2(AlOH)Al_2(SiO_4)_3$; rarely found and then only a trace.

18. Apatite: $(CaF)Ca_4P_3O_{12}$; the F may be replaced by Cl; rarely found, then only as a trace.

19. Cordierite: $H_2(Mg, Fe)_4Al_8Si_{10}O_{37}$; not conclusively found, then in only one sample.

20. Chlorite: Probably a mixture of $H_4(Mg, Fe)_3Si_2O_9$ and $H_4(Mg,Fe)_2Al_2SiO_9$; rarely found, then only as a trace.

To the above list may be added other minerals or salts more or less commonly found in soils, viz.:

Calcium compounds	Calcite	$CaCO_3$	Commonly found, especially in the lower horizons.
	Dolomite	$CaMg(CO_3)_2$	
	Gypsum	$CaSO_42H_2O$	
Iron compounds	Hematite	Fe_2O_3	Widely distributed in all soils (44B).
	Limonite	$2Fe_2O_3\,3H_2O$	
	Pyrite	FeS_2	
White alkali salts	Soluble salts, usually of Na,K,Mg, and Ca, combined with Cl, NO_3, SO_4, and in the case of Ca with H_2CO_3 or CO_3.		
Black alkali salts	Mainly Na and K, HCO_3 or CO_2.		

194. Combinations of Silicon.—The formulae of the soil-forming minerals **(193)** show that the silicon combinations are by far the most prominent in soils. Due to their low solubility and manifest complexity, a study of their combinations is difficult, consequently there are many obscurities regarding their chemistry. The large number of combinations, however, may be explained as follows: Silicon forms two series of acids, neither of which are found in the soil:

Orthosilicic acid $H_4\,Si\,O_4$

Metasilicic acid $H_2\,Si\,O_3$

These acids may be combined to form the following series:

$$2\,Si(OH)_4 = \text{Orthodisilicic acid } H_6Si_2O_7 + H_2O$$

$$3\,Si(OH)_4 = \text{Orthotrisilicic acid } H_8Si_3O_{10} + 2H_2O$$

In a similar manner, metasilicic may be combined to form metadisilicic acid $H_2Si_2O_5$ and metatrisilicic acid $H_4Si_3O_8$ It appears

that almost all of the natural silicates may be regarded as salts of these hypothetical silicic acids.

195. The Products of Chemical Action in Soils.—The products of chemical action in soil functions may be divided into two great classes, the transported and the residual or sedentary. The transported is that great mass of soluble compounds removed from the soil by various processes **(240)**. The residual is the more or less insoluble material remaining. It is the blended or assorted material resulting from rock decomposition which, after suitable periods of weathering and exposure to biologic influences, becomes an agricultural soil. The composition of the soil mass, therefore, may bear little or no relation to the composition of the minerals from which it has formed. Clarke (*Data of Geochemistry*, p. 490) compares the composition of some original rocks with their decomposition products. The results shown in Table **27** illustrate the character of variations found.

TABLE 27

ANALYSES OF ROCKS AND THEIR DECOMPOSITION PRODUCTS[3]

A = Original Rock B = Derived Soil

	Micaceous Granite Dist. of Columbia		Micaceous Gneiss Albemarle Co., Va.		Augite Andesite Rockland Ridge, Washington	
	A	B	A	B	A	B
SiO_2	69.33	65.69	60.69	45.31	50.85	58.16
Al_2O_3	14.33	15.23	16.89	26.55	12.54	15.03
Fe_2O_3	....	4.39 (with FeO)	9.06 (with FeO)	12.18	10.03	10.59
FeO	3.60			....	7.11	....
MgO	2.44	2.64	1.06	0.40	5.57	1.99
CaO	3.21	2.63	4.44	trace	9.33	4.57
Na_2O	2.70	2.12	2.82	0.22	2.37	2.56
K_2O	2.67	2.00	4.25	1.10	1.13	1.68
TiO_2	....	0.31	....	....	....	....
P_2O_5	0.10	0.05	0.25	0.47	0.76	0.43
SO_3	....	....	....	....	0.05	0.07
Organic	....	....	....	....	....	3.52
Ignition	1.22	4.70	0.62	13.75	....	....
H_2O	....	....	....	....	0.34	1.77

Another way of viewing the results of chemical disintegration and soil formation is presented by Dennison and Fry,[4] who

[3] Clarke, F. W., "Data of Geochemistry," *U. S. Geol. Sur. Bul. 770.* 1924.

[4] Dennison, I. A., and Fry, W. H., "The Chemical Alteration of Mica in the Development of the Soil Profile," *Amer. Soil Survey Assoc. Rpt. Bul. 9*, pp. 153-162. 1928.

show, in Table 28, the average composition of biotite isolated from different soil horizons as compared with that isolated from the parent rock.

TABLE 28

COMPOSITION OF MICA (PRINCIPALLY BIOTITE) FROM THE PORTER'S PROFILE
Results Expressed as Per Cent

HORIZON	DEPTH INCHES	SiO_2	Fe_2O_3	FeO	Fe_2O_3 FeO / FeO	Al_2O_3	MgO	K_2O	H_2O
A	0–4	45.1	12.1	N.D.	10.9	24 0	3 7	4.5	8.2
B_2	14–48	37.6	16.0	0.6	15.0	23.1	6.5	4.8	9.5
C_1	48–60	44.6	9.8	0.4	9.1	29.4	2.2	2.8	10.9
C_2	60–72	43.6	7.5	1.0	7.8	30.1	2.2	3.1	10.5
C_3	72–96	42.3	5.5	4.5	9.4	28.2	2.9	4.5	9.5
Rock	96↓	35.1	4.7	20.4	24.6	15.0	7.1	9.0	2.0

Both Table 27 and Table 28 tell essentially the same story. The iron compounds are oxidized. The material itself is hydrolized and the soluble compounds are removed. This point is made clearer by a study of Table 29 showing the amounts lost from certain soil-forming rocks.

TABLE 29

PERCENTAGE OF EACH ORIGINAL ROCK CONSTITUENT
LOST IN DECOMPOSITION [4a]

	GRANITE	GNEISS	DIABASE	DIORITE
SiO_2	10.50	31.90	8.48	17.43
Al_2O_3	0.46	....	....	....
FeO Fe_2O_3	....	1.30	2.42	3.53
MnO	....	....	0.32	....
MgO	0.36	0.80	0.68	4.97
CaO	0.81	4.44	1.83	9.20
Na_2O	0.77	2.68	0.50	2.17
K_2O	0.85	3.55	0.62	0.21
P_2O_5	0.04	....	0.08	....

196. The Composition of Soils.—Literally thousands of soil analyses have been made. In many cases only a few of the total number of elements have been determined, while in other cases the analyses have been restricted to a certain combination of elements. Usually a total analysis is not made. The total composition of soils in the eastern portion of the United States is shown

[4a] For chemical and mineralogical analyses of Granite, see Clarke, *Bul 770*, pp. 432-441; of Gneiss, see p. 629; of Diabase, see p. 464; of Diorite, see pp. 456-460.

See also Merrill, G. P., *Rocks, Rock-Weathering, and Soils*, pp. 195 to 202. 1906.

in Table 30. This table [5] is based on 26 samples in one case (Robinson) representing the main soil types in four provinces, and 45 samples in another case (Robinson *et al.*) representing also four provinces.

197. Variation in the Chemical Composition of Soils.—The chemical composition of soils, Table 30, shows considerable variation between the maximum and minimum content of soils from the same province. This variation may be explained on the basis of deviation of material, process of formation, topography, climatic conditions, etc. With the exception of sulphur and nitrogen, little is known about the variations of the elements occurring in lesser amounts. It may be assumed, however, that "the extremes in composition [6] with regard to major constituents are as follows":

Silica	SiO_2	97.01	to	44.15	per cent.
Iron	Fe_2O_3	16.23	to	0.33	"
Alumina	Al_2O_3	27.58	to	1.19	"
Potash	K_2O	4.07	to	0.02	"
Soda	Na_2O	2.06	to	0.01	"
Lime	CaO	1.73	to	0.01	"
Magnesia	MgO	1.93	to	0.01	"
Phosphoric acid	P_2O_5	0.22	to	0.03	"
Sulphuric acid	SO_3	0.34	to	0.02	"

198. Sampling Soil for Chemical Determinations.—The many forces and conditions concerned in the formation of a soil area naturally have an influence on the resulting material. This influence is recognized at once when an analysis is made on several samples taken from different parts of an area that is apparently uniform. The American Society of Agronomy Committee on Standardization of Field Experiments [7] points out that "Refinements of analytical methods are useless if the samples do not represent the average soil of the plot within at least rather narrow limits of error." It is realized that there is more or less variation in the individual samples, and the analyst is faced

[5] Robinson, W. O., "The Inorganic Composition of Some Important American Soils," *U. S. Dept. of Agric. Prof. Paper No. 122.* 1914.
Robinson, W. O., Steinkoenig, L. A., and Fry, W. H., "Variation in the Chemical Composition of Soils," *U. S. Dept. of Agric. Bul. 551.* 1917.

[6] *U. S. Dept. of Agric. Bulletin 551*, p. 11. 1917.

[7] American Society of Agronomy, "Report of the Committee on Standardization of Field Experiments," *Jour. Amer. Soc. Agron.*, *9*, pp. 402-419. 1917.

TABLE 30

Total Chemical Composition of American Soils to a Depth of 36 Inches, Expressed as Per Cent

Constituent	Coastal Plain Province		Limestone Valleys Province		Glacial and Loessal Province		Piedmont Plateau Province		Great Plains Province		River Flood Plains Province	
	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
SiO_2	94.50	85.30	79.35	66.49	76.86	65.68	88.57	44.15	78.85	68.74	93.29	73.25
TiO_2	.91	.71	1.28	1.01	.79	.59	1.59	.40	0.36	0.32	0.69	0.42
Al_2O_3	8.82	2.07	14.80	8.89	14.15	9.10	27.58	5.54	14.45	9.68	13.79	2.45
Fe_2O_3	1.91	0.83	5.99	4.23	5.67	3.79	16.23	1.55	5.00	2.72	4.88	0.78
MnO	.007	.004	.180	.053	.120	.022	.51	.005	.057	.031	.079	.024
Cr_2O_3	.007	.004	.018	.004	.013	trace	.025	.002	N.T.	N.T.	N.T.	N.T.
V_2O_5	.01	.01	.08	.02	.08	.02	.06	.01	"	"	"	"
Rare earths	.03	.02	.08	.01	.02	.02	.04	.01	"	"	"	"
$Zr\ O_2$	.05	.02	.08	.01	.06	.02	.08	.003	"	"	"	"
MoO_2	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	P	N.F.	"	"	"	"
NiO + CoO	?	?	"	"	.06	.04	.04	?	"	"	"	"
CuO	N.T.	N.T.	"	"	P	P	P	P	"	"	"	"
CaO	.39	38	.93	.35	1.40	.37	1.73	.08	1.08	.88	.21	.12
BaO	.004	.004	.063	.021	.53	.041	.360	.027	N.T.	N.T.	N.T.	N.T.
SrO	.03	.02	.11	.04	.05	.01	.05	.01	"	"	"	"
MgO	.19	.09	1.93	.33	1.28	.39	1.06	.09	1.12	.36	.34	.09
K_2O	.12	.10	3.58	.67	2.28	1.04	3.96	.61	2.57	2.20	1.08	.45
Na_2O	.11	.07	.82	.16	1.75	.63	1.54	.14	2.06	1.12	.12	.03
Li	P	P	P	P	P	P	P	P	N.T.	N.T.	N.T.	N.T.
Rb	.001	.001	.002	.001	.002	.001	.01	trace	"	"	"	"
Cs	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	N.F.	"	"	"	"
P_2O_5	.06	.04	.19	.16	.24	.11	.16	.05	.11	.08	.06	.05
SO_3	.13	.07	.39	.13	.18	.03	.16	.04	.20	.07	.13	.05
Ignition loss	3.22	1.74	6.08	4.63	9.52	3.13	11.83	1.41	7.11	2.28	5.18	1.53
Water at 110°C.	1.48	.48	2.38	1.40	3.39	1.28	2.90	.22	N.T.	N.T.	N.T.	N.T.
Organic matter	1.13	.29	2.87	.82	7.07	.60	2.40	.09	N.T.	N.T.	N.T.	N.T.
CO_2 (carbonates)	N.F.	N.F.	.56	N.F.	N.F.	N.F.	N.F.	N.F.	"	"	"	"
Nitrogen	.08	.01	...	...	.14	.05	...	...	.20	.07	.10	.03

N.T. = Not Tested; N.F. = Not Found; P = Present.

with the problem of securing enough samples to eliminate the variables. In other words, the number of samples to be secured will depend upon the significance to be attached to the results, the experimental error in the analyses themselves, and the physical capacity of the laboratory. Waynick and Sharp[8] studied the variation in the nitrogen and carbon content of two uniform areas of very different character. One was a silty clay loam at Davis; the other a blow sand at Oakley. The areas were slightly over one acre in size, and were sampled at 15- and at 30-foot intervals. The samples were analyzed individually and collectively. The nitrogen content of the Davis soil ranged from 0.077 to 0.124 per cent and in the Oakley soil from 0.022 to 0.063 per cent. The carbon content of the Davis soil ranged from 0.903 to 1.383 per cent and in the Oakley soil from 0.252 to 0.750 per cent. If a variation of 25 pounds per acre of nitrogen is taken as the limit and the odds are even that the results may be duplicated, the number of samples required is 100 of Davis and 61 of Oakley soil, the same limitation in the case of carbon would require 12,222 samples of Davis and 16,685 of Oakley soil. If the accuracy is limited to 100 pounds of nitrogen, the odds even, only 6 samples of Davis and 4 of Oakley soil are required. If the accuracy is limited to 500 pounds of carbon and the odds are even, 28 samples of Davis and 39 samples of Oakley soil are required. In other words, accuracy can only be secured by a great number of samples.

199. Kinds of Soil Analyses.—The chemist regards the soil as a medium for the production (directly or indirectly) of all food materials, both animal and vegetable. He regards any factor affecting the crop-producing power of the soil as a factor affecting the local or national supply of food. These factors are frequently associated with certain soil-derived plant food elements, or their combinations, and are modified by the physical, chemical, and biological properties of the soil mass. In many cases these factors can only be determined by chemical methods. The kinds of analyses usually made may be grouped as follows:

I. Total Analyses.—A total analysis may be for one or more elements, nitrogen, phosphorus, potassium, sulphur, calcium, mag-

[8] Waynick, D. D., and Sharp, L. T., "Variability in Soils and Its Significance to Past and Future Investigations. II. Variations in Nitrogen and Carbon in Field Soils and Their Relation to the Accuracy of Field Trials," *Univ. of Cal. Pub. in Agric. Sci.*, *4*, pp. 121-139. 1919.

nesium, and sometimes barium, titanium, boron, chlorine, etc. A complete soil analysis.

II. Availability Analyses.—The determination of the "so-called" availability of the soil-derived plant-food elements. The use of methods designed to measure the amount of plant-food elements in a condition assumed to be available to plants. The principal methods may be grouped under four headings:

1. Soil solutions, obtained by various means.
2. Water extractions, dilutions of the soil solution.
3. Acid extractions—the use of acids of various strengths. These methods are based on the idea that the acids have an extractive power similar to that of the plant root.
4. Replaceable bases. A determination of the replaceable bases of the soil mass, either by the use of certain salts (214) or by electrodialysis (215).

III. Biological Analyses.—The determination of biological activities by measuring chemically the amounts of carbon dioxide, ammonia, nitrate nitrogen, total nitrogen, etc., produced, fixed or changed in the soil.

IV. Special Analyses.—The determination of the soil condition by measurement of the reaction (acid, neutral or alkaline) the amount of carbon, the elements not primarily associated with plant growth, the colloidal content, toxic materials, the making of various soil tests, etc.

V. Soil Amendments Analyses.—The determination of the adaptability of materials to be added to the soil either as a carrier of plant food or as a corrective of certain soil conditions; the analysis of fertilizers, manures, lime compounds, etc.

VI. Interpretations.—The interpretation of the analysis, usually based on a combination of factors and its application to the soil from the standpoint of increasing or maintaining its crop-producing powers and arriving at a practical solution of the problem of a permanent system of fertility.

As indicated in Table 30, the soil sample may be analyzed for its total constituents. This is usually not the case. The majority of soil analyses are usually limited to a determination of the elements nitrogen, phosphorus, carbon, and potassium, sometimes calcium, magnesium, and sulphur. Frequently the analysis is limited to a determination of a certain element (for instance, nitrogen as the nitrate).

200. Limitations of a Soil Analysis.—It is practically impossible to show by chemical analysis the condition of the soil. The analyst is limited to a determination of the amounts of the bases or acids present, but he cannot, by the wildest stretch of imagination, reconstruct his analytical results into the original soil composition. As a consequence, a rather vicious and misleading practice [9] has been in vogue by chemists in reporting their findings, chiefly as the oxide of the element instead of the element itself. A much better plan is that of reporting the findings as the element in pounds (two, four, six, or eight million pounds) per acre according to the depth of sampling and characteristics of the soil.

201. What Soil Analyses Show.—A soil analysis shows, according to the kind of analysis made, the amount or amounts of certain element or elements. A total analysis shows the total amount of the elements determined but nothing more. The result of the analysis, when compared with amounts secured in other analyses and in competent hands, are frequently used as an indication of the soil's needs. An acid-soluble (strong or weak, organic or inorganic) or water-soluble analysis gives a better indication of the ability of the soil to support plant growth than a total analysis, merely because it approximates conditions as the plant finds them.

202. Interpretation of a Chemical Analysis.—The old idea that the soil could be regarded as a storehouse of plant food elements, with a value to be assessed according to the total amount of the elements present, has no place in the present conception of soils. No matter what conclusions may be drawn from a single analysis or a series of soil analyses, objection may be raised to them, particularly if the conclusions are in regard to plant growth.[10] The situation is further complicated by the difficulties encountered in securing an absolutely representative soil sample. Experience, however, has shown that there is a general relationship existing between a great number of chemical soil analyses, of mechanical soil analyses **(98)**, and crop response, and that certain deductions may be drawn that in the main will be of value.

[9] An excellent discussion regarding the "Statement of Analyses" is given by Clarke (**195**).

[10] Hoagland, D. R., "Soil Analysis and the Soil and Plant Interrelations," *Cal. Agric. Expt. Sta. Circular 235.* 1922.

203. Soil Tests.—Chemical analyses are the basis for a practical interpretation of soil phenomena by means of soil tests, some of which are chemical in nature. These tests are usually qualitative, designed to answer a certain question, and are in many cases reduced to extreme simplicity.

It must be remembered that, however simple the test, the interpretation from the broadest standpoint is an entirely different matter. Usually the interpretation involves the characteristics, the history, topography, yields, etc., of the soil itself,[11] and the final conclusion is based on results secured from soils under similar conditions.

[11] For various soil tests and their interpretation see: Briggs, L. J., "Electrical Instruments for Determining the Moisture, Temperature, and Soluble Salt Content for Soils," *U. S. Bur. of Soils. Bul. 15.* 1899. 35 pp.

See citations under Acidity, page 198.

Hoffer, G. N., "Testing Corn Stalks Chemically to Aid in Determining Their Plant Food Needs," *Indiana Agric. Expt. Sta. Bul. 298.* 1926. 31 pp.

Welton, F. A., Morris, V. H., and Gerdel, R. W., "Corn Stalks vs. Field Plots as a Guide to the Fertility Requirements of the Corn Crop," *Ohio Agric. Expt. Sta.* (Wooster) *Bul. 397.* 1926.

Spurway, C. H., "Test Soils for Water Soluble Phosphorus," *Mich. Agric. Expt. Sta. Quart. Bul.*, *9*, pp. 64-67. Nov., 1926.

CHAPTER 16

THE CHEMICAL PROPERTIES OF SOILS

Due to the fact that the chemical, like the physical, properties are closely correlated, it is difficult to clearly separate them. We may, however, divide them into two groups as follows:

I. General Chemical Properties:
- Oxidation
- Reduction
- Hydration
- Carbonization
- Solution

In this group the properties are more or less independent of each other. The chemical activities of this group, however, lead to other and more specific properties that have a marked (but at the present not a clearly defined) influence on plant growth.

II. Chemical Soil Effects:
- Ionization and adsorption
- Reaction
- Acidity
- Alkalinity
- Buffer action
- Base exchange

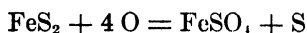
The chemical properties listed under Group II are the result of chemical, physico-chemical, bio-chemical, and bio-physical soil processes. They are extremely complex, extremely involved, and the separation of the different processes is more implied than real.

General Chemical Properties

204. Oxidation. The process of oxidation is the introduction of oxygen into a compound. As oxygen is the most active element of the air, and as the air content of the soil plays such an important function in plant production, it is but natural that it may influence many of the soil functions. Free air acts principally upon iron compounds (the sulfides, carbonates and silicates) in rocks (**44,** *II*), causing a change in color and in solubility. Thus the sulfide is oxidized to the sulfate and then to ferric oxide and sulfuric acid. The iron containing minerals, especially the micas,

garnets, etc., are particularly affected. As the process continues, the mass easily crumbles.

Active oxidation is conditioned on the presence of moisture; the soil, however, usually contains a sufficient amount to support the process. Oxygen is soluble to a certain extent in water, consequently is carried into the soil by percolation.[1] The common example of oxidation is that of pyrite to the sulfate:

$$FeS_2 + 4\,O = FeSO_4 + S$$

In the soil the process of oxidation is greatly stimulated by the presence of biological life. The roots of plants are not simply absorbing organs but possess the power, through oxidation[2] and otherwise, to make changes, usually beneficial in the soil ingredients. Thus oxidation plays an important part in the transformation of both inorganic and organic soil compounds.

205. Reduction.—The reversal of the oxidizing process is usually referred to as reduction. Under certain conditions oxygen will be removed from some salts. Thus hematite, Fe_2O_3, may lose two molecules of oxygen and be reduced to ferrous oxide, FeO. In the soil the chief agency is organic acids, whose great affinity for oxygen enables them to take part or all of it from certain compounds, especially iron salts. Thus the drab color of soils under peat areas is usually due to a reduced condition of the iron.

The micro-organic population of the soil is dependent upon a supply of oxygen. In case their air supply is cut off they may be able to secure their necessary oxygen from the mineral nutrients of the soil solution. Thus the oxygen of nitrates is assimilated and the nitrogen is allowed to escape into the atmosphere. In like manner sulfates are reduced to hydrogen sulfide and the sulphur lost.

Organic matter may reduce ferric to ferrous compounds and sulfates to sulfides. Pyrite, dissolved away from surface rocks, may reappear as marcasite elsewhere. At the surface ferrous salts yield the insoluble ferric hydroxide; in the soil, by reduction,

[1] Russell and Richards (*Jour. Agric. Sci.*, *9*, pp. 309-337; 1919) show that rain brings down a large amount of oxygen. They estimate (p. 329) that the equivalent of 66.4 pounds is deposited annually on each acre in England.

[2] Schreiner, O., and Sullivan, M. X., "Studies in Soil Oxidation," *U. S. Dept. of Agric. Bur. of Soils Bul.* 73. 1910.

Van Hise, C. R., "A Treatise on Metamorphism, Oxidation," *U. S. Geol. Sur. Monograph 47*, pp. 461-473. 1904.

the solubility is partly restored and in the form of ferrous bicarbonate the iron may be more or less washed away.

206. Hydration.—The action of hydration is the union of water with chemical compounds. A familiar example of hydration is the union of burned lime with water, $CaO + H_2O = Ca(OH)_2$. In the process of weathering certain of the common minerals unite with water, which produces not only a change in the chemical composition but in the physical character of the mineral such as to aid in its decomposition. The decomposition products of most soil-forming minerals are strongly hydrated. One result of this process is the marked change of color due to the hydration of iron.

The action of hydration is always accompanied by the liberation of heat and an increase in bulk. Merrill [3] calculated that the transition of a granite rock into arable soil, provided such transition takes place without loss of material, is attended by an increase in bulk of 88 per cent. In rocks as a class, hydration affects the volume from a very small per cent to as much as 160 per cent; in general the increase is less than 50 per cent. For instance, when anhydrite ($CaSO_4$) is hydrated and changed to gypsum ($CaSO_4 \cdot 2H_2O$) the increase in bulk may cause a marked change in the topography of the overlying area. In the case of the soil mass, notable increase in volume does not occur if the pore space is ample.

Hydration in the soil takes place in connection with carbonation and solution. In so far as the soil water is consumed in the formation of new compounds, this portion cannot be used in other phenomena. The process, however, usually makes the compound more soluble, consequently hydration is a companion process of solution.

Dehydration [4] is the opposite of hydration, namely, the removal of water, or a limitation of the hydration porcess. It is of more interest geologically than edaphologically. Its effect on iron compounds may be a possible factor in causing color changes.

207. Carbonation.[5]—The process of oxidation, especially of organic substances, tends to produce a concentration of carbon

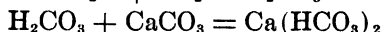
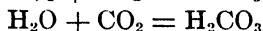
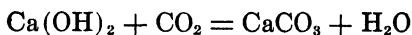
[3] Merrill, G. P., *A Treatise on Rocks, Rock-weathering, and Soils*, p. 188. The Macmillan Co., New York, 1913. 400 pp.

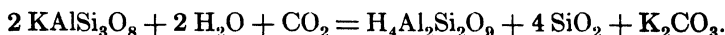
[4] Van Hise, *ibid.*, "Hydration and Dehydration," pp. 481-483.

Crosby, W. O., "On the Contrast of Color of the Soils of High and Low Latitudes," *Amer. Geologist*, *8*, pp. 72-82. 1891.

[5] Van Hise, *ibid.*, "Carbonation," pp. 473-480.

dioxide in the soil horizons (**124**). The carbon dioxide is quite soluble in water. The union of carbon dioxide with soil water actively increases the solvent action of the latter, forming carbonates and bicarbonates with the various rock and soil bases. The process may be illustrated by the familiar carbonation of the hydrate of lime and the formation of the bicarbonate.

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$$
$$H_2O + CO_2 = H_2CO_3$$
$$H_2CO_3 + CaCO_3 = Ca(HCO_3)_2$$

In the case of soil-forming rocks this is dominantly accomplished by the substitution of carbonic for silicic acid; for instance, the decomposition of orthoclase with the formation of kaolin,

$$2\,KAlSi_3O_8 + 2\,H_2O + CO_2 = H_4Al_2Si_2O_9 + 4\,SiO_2 + K_2CO_3.$$

To some extent carbonates are also formed (1) by the substitution of carbonic for other acids, *i.e.* phosphoric acid; (2) by the union of carbon dioxide with oxides not united with other acids, *i.e.* ferrous oxide in magnetite.

The process of carbonation has a direct relation to vegetation, as the latter is the source of supply for the reactions involved. The reaction is dependent upon moisture and temperature; hence is most rapid in the tropics, least in the frigid zones, and varies in the temperate zones with the moisture supply; consequently is less in the arid than in the humid areas.

The destructive action of water charged with carbon dioxide on lime rock is well known. Its effect is due largely to a reduction of the mass of the hydrates of the hydrolyzed bases by the formation of bicarbonate. In the case of the feldspars, the decomposition results in the formation of clays. In the case of granite soils, the silica, set free, remains almost wholly in the resulting soils. In the case of limestones there is a more or less rapid change of the carbonate to the bicarbonate and its removal by leaching.

208. Solution.—It is a well-known fact that practically all minerals are more or less soluble. The solvent power of water is further increased by the presence of soluble gases washed from the atmosphere (**112**), by accumulations of carbon dioxide or other gases in the soil and by the presence of various soluble materials in the soil itself.

Thus we find that in nature all the elements in the rock and

soil minerals are being dissolved practically all the time. However, they dissolve at various rates depending upon the strength and abundance of the active compounds in solution and upon the solubility of the constituent minerals. The process is continually being influenced by the complicated actions of life processes.

As the presence of water is required for practically all chemical processes, solution may be said to be the result of the combined processes of oxidation, reduction, hydration, and carbonation. The last two are the principal processes that bring dissolved mineral substances into the soil solution. As a consequence, solution is a factor subject to climatic influences and has a marked influence upon soil characteristics. For example, Emerson [6] shows that the reddish Orangeburg soils extend through the Coastal Plain from the Carolinas into Texas, but as they extend into the drier areas of Texas their lime content becomes higher. Another interesting example is seen in Washington where a belt of fine-grained soils extend from a very dry to a practically humid region. The soils in the dry region are sandy but as the region extends into areas of greater rainfall the soils change to loams because the sand grains have decomposed in part to clays. Hilgard [7] compares soils subject to different quantities of rainfall as shown in Table 31.

TABLE 31

EFFECT OF CLIMATE ON THE CHEMICAL COMPOSITION OF SOILS
Results in Per Cent

	SOILS FROM HUMID REGION	SOILS FROM TRANSITION REGION	SOILS FROM ARID REGION
	Average 696 Samples	Average 178 Samples	Average 573 Samples
Insoluble residue + SiO_2	88.21	83.50	75.87
Potash	.21	.33	.67
Soda	.14	.32	.35
Lime	.13	.70	1.43
Peroxide of iron	3.88	2.08	5.48
Phosphoric acid	.12	.21	.16

These results tend to explain in part why the fertility of arid soils is so pronounced when they are supplied with water. Appar-

[6] Emerson, F. V., *Agricultural Geology*, p. 71. John Wiley and Sons, New York, 1920. 319 pp.

[7] Hilgard, E. W., *Soils*, p. 377. 1911 ed.

ently they are quite different from the soils of humid regions and have not been subject to a removal of their constituents.

Solution is affected by the porosity of the mass, the rate at which the water moves, and the temperature. Porosity affects the free movement of the water, and exposes the surface of the material to water action. Slowly moving water, all other factors being equal, will dissolve more than rapidly moving water. Temperature is a somewhat minor factor, but is important during long periods, as the higher the temperature the more active the chemical effect.

Laboratory experiments and field observations show that practically all minerals, certainly those of importance in soil formation, are attacked by water and carbonic acid. The pyroxemes (mixtures of $MgSiO_3$ and $FeSiO_3$ or $R_2Si_2O_6$) and amphiboles (hornblende) are most soluble, being followed in descending order by plagioclase, orthoclase, and the micas; muscovite, a representative of the micas, being the most resistant. Even quartz is not quite insoluble, and the corrosion of quartz pebbles in conglomerates is not uncommon. Among the commoner accessories apatite and pyrite are the most easily decomposed, magnetite is less attacked, and such minerals as zircon ($ZrSiO_4$), corundum (Al_2O_3), chromite ($FeCr_2O_4$), ilmenite ($FeTiO_3$), etc., tend to accumulate with little alteration in the sandy residues.

The effect of water upon soil-forming rocks may be divided into several phases. First, it partially dissolves the more soluble compounds, liberating colloidal silica and forming the carbonates of calcium, magnesium iron, and the alkalies. The iron carbonate is almost instantly oxidized **(204)**, forming a visible rusty coating or precipitate of ferric hydroxide. The lime and alkali salts remain partly in solution, to be washed away, with much of the dissolved silica. The second phase is represented by hydration **(206)** of the undissolved residues. The feldspars are transformed into kaolin **(207)** and the magnesium minerals into talc or serpentine.

$$\underset{\text{Olivine}}{2Mg_2SiO_4} + 2H_2O + CO_2 = \underset{\text{Serpentine}}{Mg_3H_4Si_2O} + \underset{\text{Magnesite}}{MgCO_3}$$

Chemical Soil Effects

The influence of oxidation, reduction, hydration, **carbonation**, and solution is mainly one of decomposition, resulting in a more or less continuous loss of the constituents in the soil mass. But

the chemical state of the mass has a tendency toward a certain equilibrium. It has passed through many centuries of climatic effects and still retains a certain amount of materials capable of being extracted by plants. Apparently the soil possesses certain properties that enable it to withstand or combat the ravaging effects of nature, yet these properties are not of sufficient force to absolutely prevent the plant from extracting the materials needed for its sustenance. A complete discussion of the points involved is impractical at this stage, due to the fact that they apparently tax the ingenuity of both the chemist and the physicist for explanation. Further, opinions as to the explanations do not always agree. In order that the student may not become hopelessly involved, only the essential facts will be presented, to show the complexity of the chemical properties of soils.[8]

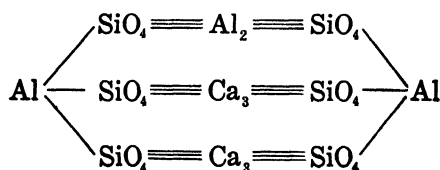



Fig. 17.

209. The Combinations of Soil Elements.—From the foregoing it becomes evident that the soil is an extremely complex chemical mixture; in fact, it is built up of complex compounds. Clark (*Bul. 770,* p. 612) shows the constitutional formulæ of minerals to conform to the general structure (for instance, garnet) of Figure 17.

[8] For a more complete discussion the student is referred to the following general references:

Michaelis, L., *The Effect of Ions in Colloidal Systems.* Williams and Wilkins Co. Baltimore. 1925. 108 pp.

Colloid Symposium Monograph, 419 pp. (1) "Papers and Discussion Presented at the First National Symposium on Colloid Chemistry." 1923. Published by Dept. of Chemistry, University of Wisconsin, Madison, Wis. (2) "Papers Presented at the Second National Symposium on Colloid Chemistry at Northwestern University." 1924. Edited by H. N. Holmes and published by the Chemical Catalog Co., Inc., New York, as *Colloid Symposium Monograph Vo. 2.* 1925. 308 pp. (3) "Papers Presented at the Third National Symposium on Colloid Chemistry at the University of Minnesota." 1925. Edited by H. N. Holmes and published by the Chemical Catalog Co., Inc., New York, as *Colloid Symposium Monograph Vo. 3.* 1926. 323 pp. (4) "Papers Presented at the Fourth National Symposium on Colloid Chemistry. Mass. Inst. of Technology." 1926. Edited by H. B. Weiser and published by the Chemical Catalog Co., Inc., New York, as *Colloid Symposium Monograph Vo. 4.* 1927. Approx. 300 pp.

We may rewrite this to show that the soil consists of such complex alumino silicates as shown in Fig. 18.

These or similar arrangements in the mass will be spoken of as the soil complex. In other words, the combination of soil elements consists mainly of an alumino-silicate nucleus, combined with various basic and acidic elements or combination of ele-

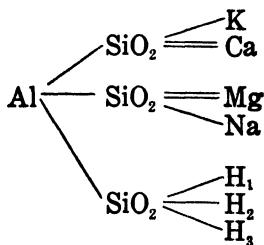
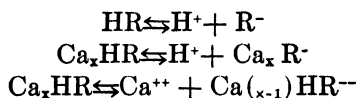



FIG. 18.

ments. Further, as indicated by the base H_1, H_2, and H_3, the different bases may vary in their relationship to the nucleus and to the surrounding medium.

210. Ionization of Soil Compounds.—The soil particle is surrounded by, and more or less soluble in, a moisture film. The film therefore may contain a wide variety of ions, from the slightly dissociated silicic acid to the highly dissociated nitrate or chloride. As the soil particle tends to approach a state of true solution there may be all degrees of ionization. For instance, the silicates, represented by R, may ionize in various ways:

$$HR \rightleftarrows H^+ + R^-$$
$$Ca_xHR \rightleftarrows H^+ + Ca_x R^-$$
$$Ca_xHR \rightleftarrows Ca^{++} + Ca_{(x-1)}HR^{--}$$

As ionization in the case of the soil particle is closely associated with surface phenomena and the particle itself may be in various conditions in respect to the soil moisture, let us consider the most active, namely, the soil colloid. According to Langmuir's theory,[9] "an atom within a solid exerts its chemical attraction in all directions. An atom in a surface has unsatisfied attraction or chemical affinity reaching out into space for a distance comparable with an atomic diameter at least and this attraction may

[9] Millard, E. B., *Physical Chemistry for Colleges*, p. 359. McGraw-Hill Book Co. New York, 1921. 411 pp.

bring about a condensation of molecules upon a surface." Therefore we have two forces, dispersion and attraction, influencing the distribution of the ions, and these two tend to regulate the distribution of the zone of ionization. The nucleus of the gel (spoken of by some writers as the "acidoid") is thus surrounded by a layer of concentrated ions.

The idea is that an electrical double layer is formed at the surface of the solid particles. These layers are considered in the mathematical sense [10] as real surfaces. It may be assumed that a solid particle suspended in a liquid and surrounded by an electrical double layer has a certain similarity to an electrical spherical condenser. The exterior layer is apparently formed of numerous cations, the interior of a single (or a few) anions of huge dimensions which contains numerous negative charges at the superficies. The influence of ionization on the chemical properties of the soil is very wide in scope. They practically control the effects noted in the balance of this chapter.

211. The Ionized Layers.—The ionized portion surrounding the particle has two layers, an outer and an inner. The ions on the surface dissociate but by attraction and dispersion are held (adsorbed) [11] at varying distances. In the case of the soil gel, the anion is held closely at the surface, while further out in the solution the cation is also held, but in a freer state, consequently cannot diffuse away. Thus we have two distinct layers of ionization, spoken of as the Helmholtz double layer, which may be diagrammatically represented as in Figure 19.

[10] Michaelis, L., *The Effect of Ions in Colloidal Systems.* Williams and Wilkins Co., Baltimore, Md., 1925. 108 pp.

[11] The term adsorbed as used here refers to the mechanics of the process. There is no clear definition in the soils literature as to the process or its limitations. Investigators have used the terms absorption and adsorption rather loosely and have not agreed as to whether the process is physical, chemical or a combination of both. Some of the more recent work, notably by Hissink, Gedroiz, and Kelley and Brown, has shown that measurable amounts of bases are held by the soil particles in this condition. Hissink concludes that the absorbed bases are as available to plants as are the water-soluble bases, *i.e.*, the bases in solution in the soil moisture.

See in this connection:

Hissink, D. J., "Methods for Estimating Absorbed Bases in the Soil and the Importance of These Bases in Soil Economy," *Soil Science*, 15, pp. 269-276. 1923.

Gedroiz, K. K., "The Absorbing Capacity of the Soil and Zeolitic Bases," *Zhur. Opit. Agron.* (Jour. of Experimental Agronomy), *17*, pp. 472-527. 1916. Translation.

Kelley, W. P., and Brown, M. S., "Replaceable Bases in Soils," *Cal. Agric. Expt. Sta. Tech. Paper 15.* 1924.

McClendon[12] shows that the layer increases in thickness with dilution of the electrolyte. In a 0.1 N. KCl solution, the thickness of the layer was found to be 0.194×10^{-6}cm., while in a 0.001N. KCl solution, it was 0.325×10^{-6}cm.

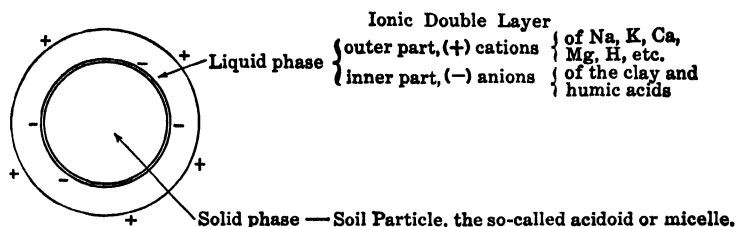



FIG. 19.

The tendency of the soil particle is apparently to maintain a constant concentration of ions in the Helmholtz double layer. If particles are lost to the soil solution, or are removed by plants, the particle itself has a tendency to replace the ions lost by the same kind; or, failing in this, by some other ion, for instance, an H ion. On the other hand, the soil particle has a tendency to regain or remove from the soil solution whenever possible materials similar to those lost to it. There is a constant exchange going on between the particle and the surrounding solution, the exchange taking place through and mainly because of the Helmholtz double layer.

212. Electrical Phenomena.[13]—The adsorption of the cations and anions, each carrying an electrical charge (not free electricity but capable of responding to certain electrical phenomena), leads to an electrical potential at the surface. Therefore, if the layer contains an unequal distribution of ions, the whole may be negatively or positively charged. As unlike charged particles attract and like charged particles repel, the charge of the particle has a marked influence on both the physical and the chemical properties.

[12] McClendon, J. F., "On the Thickness of the Helmholtz Double Layer," *Science*, *66*, p. 200. Aug. 26, 1927.

[13] If particles of neutral blood charcoal are placed in pure water, the particles assume a negative charge and there are free H^+ ions in the solution. The OH^- ion is tightly held at the surface of the particle, the H^+ ion is more free. Thus the charge of the particle is due to the charge of the inner surface of the Helmholtz double layer, the charge of the solution is due to the influence of the outer surface of the layer.

Arrhenius [14] shows that clays of different origin and different reaction have the same iso-electric point, and the curve obtained by plotting the rate of settling against the hydrogen-ion concentration has the same course as that of gelatin. The clay acts as an amphoteric electrolyte and apparently can combine stoichiometrically with either acid or base. Further, the colloidal fraction apparently remains negatively charged,[15] at least within a hydrogen-ion of (pH 2.1 to 12.7), the stability apparently being due to the nature and concentration of the cations present in the solution.

213. Donnan Equilibrium Effect.—If a diffusible substance (for instance, sodium chloride) is placed on one side of a semipermeable membrane, it will diffuse through and establish an equilibrium of concentration on both sides. As a result, the potential on both sides will be equal. If, however, a non-diffusible substance, *i.e.* $CaCo_3$, is placed on one side of the membrane, the ions of the non-diffusible substance will act as repellants of the diffusible ions, and there will be an unequal potential. This effect is called the Donnan equilibrium [16] effect. The presence of a membrane, however, is not necessary. The alumino-silicates, the iron and calcium compounds of the soil particle act as non-diffusible ions, causing an unequal distribution of ions at the surface of the particle and in the free soil solution, the concentration being greatest at the surface. Parker [17] claims that at present there is no definite proof that this effect exists in the soil. He states, "Granting that it does exist, there is no proof as to what is the concentration of the solution at the surface of the particle."

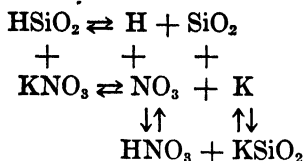
214. Base Exchange.—If an acid soil is treated with a neutral salt solution, the base is fixed by the particle, the acid is freed and titratable acidity is developed in the liquid. The following general reaction takes place. In other words,

[14] Arrhenius, O., "Clays as an Ampholyte," *Jour. Amer. Chem. Soc.*, *44*, pp. 521-524. 1922.

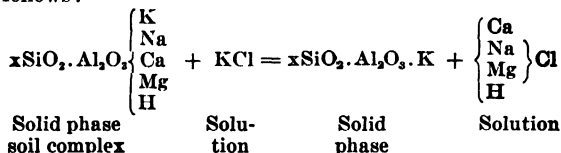
[15] Dayhuff, W. C., and Hoagland, D. R., "The Electrical Charge on a Clay Colloid as Influenced by Hydrogen-ion Concentration and by Different Salts," *Soil Science*, *18*, pp. 401-408. 1924.

[16] Donnan, F. G., "Discussion at the Faraday Society Symposium on Base Exchange," *Trans. Faraday Society*, *20*, Part 3, p. 572. 1925.

[17] Parker, F. W., "Plant Growth and the Absorption of Phosphorus from Culture Solutions of Different Phosphate Concentrations," *Soil Science*, *24*, pp. 129-146. 1927.

$$
\begin{array}{ccccc}
HSiO_2 & \rightleftarrows & H & + & SiO_2 \\
+ & & + & & + \\
KNO_3 & \rightleftarrows & NO_3 & + & K \\
 & & \downarrow\uparrow & & \uparrow\downarrow \\
 & & HNO_3 & + & KSiO_2
\end{array}
$$

there has been an exchange [18] in the position of the cations with the formation of a highly and a weakly ionized compound. Due to the fact that the acidoid may not ionize completely, the reaction is not according to the usual stoichiometrical proportions, neither does it go to completion for a definite concentration. Further, there is a variability in solubility of the salts of the gel according to the type of cation in the salt (K, Ca, H_1, H_2, etc.); hence there is a variability of hydration. A relatively slightly hydrated cation as Ca will be able to approach much closer to the anion on the inner surface of the Helmholtz double layer than a highly hydrated cation like Na. As a result, we find that, in spite of the fact that the gel possesses a fixed dissociation capacity which is imparted to the surface ionization in the double layer, there is an exchange of ions between this layer and the surrounding solution; further, that this exchange of bases takes place in acid, neutral, or alkaline soils. Kelley and Brown [19] show that the replaceable bases [20] may be considered as residing in the clay or smaller soil fractions. Also that they are present, not in a state of physical adsorption, but as chemical compounds, probably as complex alumino-silicates which have been formed as a result of weathering. It becomes apparent there-

[18] The soil complex, Fig. 18, page 189, may be used to represent the interchange as follows:

$$
\underset{\text{Solid phase soil complex}}{xSiO_2.Al_2O_3\left\{\begin{matrix}K\\Na\\Ca\\Mg\\H\end{matrix}\right.} + \underset{\text{Solution}}{KCl} = \underset{\text{Solid phase}}{xSiO_2.Al_2O_3.K} + \underset{\text{Solution}}{\left\{\begin{matrix}Ca\\Na\\Mg\\H\end{matrix}\right\}Cl}
$$

[19] Kelley, W. P., and Brown, S. M., "Replaceable Bases in Soils," *Univ. of Cal. Publications Tech. Paper 15.* 1924.

[20] For a general discussion of base exchange in soil see:

"Base Exchange in Soils. A General Discussion by the Faraday Society," *Transactions of the Faraday Society, Vol. 20.* 1924.

"A Symposium on Base Exchange Phenomena in Soils, A General Discussion by the American Society of Agronomy," *Jour. Am. Soc. Agron., 18,* pp. 450-515, 1926.

Papers Presented in the Transactions of the Second Commission of the International Society of Soil Science. Gröningen. 1926.

fore that, through this base exchange phenomena, the soil has the power to recuperate some of the materials resulting in its decomposition.

Base exchange is partially dependent upon the degree of hydration. The effect is not fully understood. It is known, however, that hydrolysis may involve both the exchange complex and the various crystalline particles. Ground rock masses may yield alkaline solutions by hydrolysis. If sodium, for instance, forms a considerable portion of the replaceable base, it tends to undergo hydrolysis with the resulting formation of sodium hydroxide. Other bases, Ca, etc., may also undergo the same effect. The hydrolytic effect may possibly dominate the reaction of a carbonate-free soil whose exchange complex is slightly unsaturated with bases.

The phenomena of ion exchange in soils appears to be subject to the principles of mass action and chemical equilibrium,[21] but the several cations differ considerably in their replacing activity. The evidence at present indicates that the activity of the ions stands in the order of

$$H > Ca > Mg > K > Na.$$

It appears also that the exchange action is partially reversible, that is, the H ions may be displaced from the exchange complex by the base of a neutral salt solution. In fact, an acid soil may be converted into an alkaline soil [22] by treatment first with sodium chloride and then with distilled water.

The property of base exchange appears to be common to all soils. If a solution containing salts is brought into contact with the soil, the reaction takes place rapidly and equilibrium is attained in a few minutes. A part of the base of the salt displaces an equivalent amount of the soil bases. The former passes out of solution and becomes a component of the soil complex; the latter pass into solution and may then be leached away, provided of course that insoluble compounds are not formed. When chlorides and nitrates are used, the salts formed by base exchange are of high solubility, but the use of solutions of carbonates and

[21] Truog, E., "The Cause and Nature of Soil Acidity, with Special Regard to Colloids and Adsorption," *Jr. Phys. Chem.*, *20*, pp. 457-484. 1916.
Hissink, D. J., "Beitrag zur Kenntnis der Adsorptionvargange in Boden," *Internatl. Mitt Bodenk.*, *12*, pp. 81-172. 1922. Also in *Soil Science*, *15*, pp. 269-276. 1923.

[22] Cummins, A. B., and Kelley, W. P., "The Formation of Sodium Carbonate in Soils," *Cal. Agric. Expt. Sta. Tech. Paper 3.* 1923.

phosphates leads to the formation of insoluble precipitates. A given soil usually contains a fairly definite amount of total exchangeable base, but different soils may contain rather widely differing amounts. The reactive constituents reside chiefly in the clay fraction, while the coarser materials play a minor and usually a relatively unimportant part.

The amount of soil base that is replaced depends upon the cation used. For example, an equivalent amount of potassium salt will replace more calcium than a sodium salt. Repeated treatment with each salt will replace all the calcium, the potassium completing the reaction more quickly. The properties of the soil mass are altered by different cations. Those having the lowest replacing power (for instance, sodium) tend to produce a high degree of dispersion which results in a sticky impenetrable condition in the mass. Those having the greatest replacing power (for instance, calcium) and are least hydrated tend to produce the opposite (coagulating) effect.

TABLE 32

BASES AND ACIDS EXTRACTED FROM COLLOIDAL SOIL MATERIALS BY BASE EXCHANGE REAGENTS AND BY ELECTRODIALYSIS

(Results expressed as per cent.)

KIND OF COLLOID	TREATMENT OF COLLOID	SiO_2	Fe_2O_3	Al_2O_3	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	SO_3
Sharkey	Extraction with $^n/_1$ NH_4Cl	None	Trace	Trace	0.016	1.33	0.36	0.13	0.03	Trace	N.D.
	Extraction with $^n/_{20}$ HCl	0.14	0.35	0.80	0.019	1.39	0.41	0.14	0.03	0.06	0.04
	Electrodialysis	0.05	0.14	0.29	0.017	1.33	0.37	0.16	0.04	0.04	0.04
Norfolk	Extraction with $^n/_1$ NH_4Cl	None	Trace	Trace	0.002	0.15	0.04	0.07	0.02	Trace	N.D.
	Extraction with $^n/_{20}$ HCl	0.09	0.05	0.52	0.002	0.16	0.03	0.08	0.01	0.01	0.04
	Electrodialysis	0.02	0.03	0.20	0.002	0.16	0.05	0.06	0.01	0.01	0.04

N.D. = Not determined.

215. Electrodialysis.—The ionizable substances at the surface of the soil particle (acidoid) are affected by the electric current and may be removed by the process of electrodialysis. Matson [23]

[23] Matson, S., "Electrodialysis of the Colloidal Soil Material and the Exchangeable Bases." *Jour. Agric. Resch. 33*, pp. 553-567. 1926.

For an extended review of methods, see Humfeld, H., and Alben, A. O., "Electrodialysis of Soils."

1. "A Study of the Method," *Jour. Amer. Soc. Agron., 19*, pp. 984-993. 1927.
2. "Choice of Electrodes," *Jour. Amer. Soc. Agron., 20*, pp. 36-59. 1928.

shows that the quantity of bases which can be removed is fairly definite and that the order in which they appear in the cathode chamber is about as follows: Ca, K, Na, Mg, Al, Mn, and Fe. He shows the relation of base exchange and electrodialysis on two soil colloids in Table 32 (page 195).

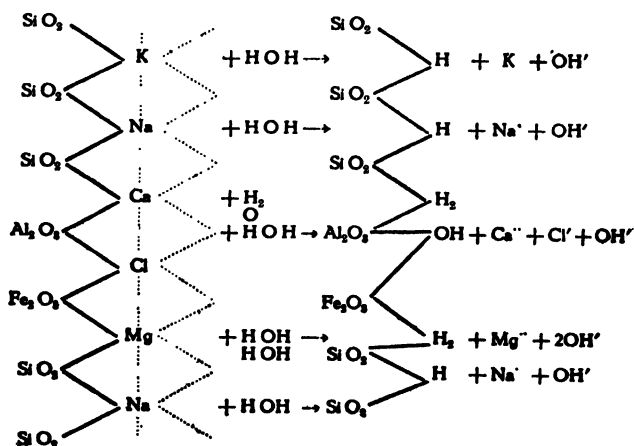
CHAPTER 17

SOIL REACTION

The majority of agricultural plants grow best in a soil having a neutral reaction. Most of them will grow in soils slightly alkaline or slightly acid soils. A few require either an alkaline or acidic reaction, but practically all are injured by excessive alkali or acid.

Unfortunately, our agricultural soils are usually not in a neutral state. Soils developed under humid conditions are usually acidic; tillage and cropping tend to make them more so. Soils under arid conditions are usually alkaline. Both conditions are capable of control. Hence the extensive studies on the nature and cause of soil acidity and soil alkalinity.

Understanding soil reaction involves the principles of ionization, hydrolysis, adsorption, base exchange, etc., in fact practically all the chemical phenomena of soils. The cause is undoubtedly the effects of weathering (primarily by carbon dioxide charged waters) modified by the presence or absence of organic matter.

The hydrolyzing action of water on the surface of a theoretical soil particle with the production of an acid or alkaline reaction is symbolized by Oden [1] as follows:

[1] Odén, Sven, "Discussion on Soil Acidity," *Trans. 2nd Commission of the Int. Soc. of Soil Science.* Gröningen (Holland), Vol. B, pp. 10-29. 1927.

The dotted lines denote unsaturated [2] residual affinities, the full lines saturated crystallographical bonds without any definite numerical significance or relation to chemical affinity. Each atom develops affinities in six directions in space.

As a result, we find that H· as well as OH′ ions from the water may be fixed at the surface of the particle which will develop into an acid or alkaline affinity point. For minerals with SiO_2 in excess the fixation of H· ions is dominant, while with minerals with Fe_2O_3 or Al_2O_3 in excess the fixation will be OH′ ions. The action depends on (1) the chemical nature of the atoms and the crystallographical structure of the mineral, (2) on the rapidity of the hydrolyzing process, (3) on the extent the H· and OH′ ions again dissociate from the surface to form an outer layer of movable ions, (4) on the ability of the H· and OH′ to break up the surface bonds more completely, thus forcing SiO_2, Al_2O_3, etc., to pass into the fluid, either as ions or as colloidal particles surrounded by ions, and (5) on the ability of the particles to obtain sufficient electrical charge to be stable and not unite with other particles. If the solution is moved away, as in the case of humid soils, the tendency is toward an acid reaction. If the solution is concentrated the tendency is toward alkalinity.

216. Acidity.—Possibly no one soil phenomena has received as much attention, in the literature of soils, as that of acidity. Practically one-fourth of the scientific soils problems have been connected with some phase of this subject. It has long been known that many soils, reacting acid to litmus, became neutral and more productive on the addition of lime. Such soils are commonly called "sour"; the chemist substituted the word acid.[3]

[2] The term saturation is used from both the physical and chemical viewpoint. Physically the soil mass may be filled (saturated) to its utmost capacity with water. Chemically the acidoid may be saturated by an exchange of bases. The acidoid, however, may contain ionizable hydrogen among its cations. When it does the soil mass is spoken of as *unsaturated*. An unsaturated soil is usually an acid soil. If, however, there is no ionizable hydrogen in the acidoid, or the whole absorptive power of the soil for metallic cations is satisfied, the soil mass is considered as saturated.

[3] For an extensive and general review of soil acidity see:

Frear, W., "Sour Soils and Liming," *Penn. Dept. Agr. Bul. 261*. 1915. 221 pp.

Ames, J. W., and Schollenberger, C. J., "Liming and Lime Requirement of Soils," *Ohio Agric. Expt. Sta. Bul. 306*. 1916. 116 pp.

Hardy, F., "Soil Sourness—Its Meaning and Significance," *West Indian Bulletin 19*. 1922.

Stoklassa, J., and Doerell, E. G., *Handbuch der biophysikalischen und biochemischen durchforschung des boden*. Paul Parey, Berlin, 1926. 782 pp.

At present there is no clear definition of soil acidity.[4] We find it referred to in varying terms, for instance, latent, active, apparent, real, positive, negative, immediate, continuous, adsorptively saturated or unsaturated; free, exchange or hydrolytic, etc. Undoubtedly there are many kinds and degrees. Under some conditions the soil apparently contains free acids, at least the soil has an excess of hydrogen over hydroxyl ions,[5] a condition that indicates acidity from the chemical viewpoint. On the other hand, Page [6] shows that soil acidity is a function of, or associated with, the absorbing properties of the soil. Apparently soil acidity is a condition that, whatever its cause, may from the practical standpoint be corrected by the application of lime.

A neutral soil may be made acidic by merely subjecting it to the process of dialysis, and the change from neutrality to acidity may be hastened by conducting the dialysis under the influence of the electric current (215). Kelley and Brown [7] subjected a soil having a pH of 6.95 [8] to electro-dialysis, through parchment paper, for a period of five days and increased the acidity to pH 4.50. In this period the exchangeable calcium had been reduced from 0.436 per cent to 0.280 per cent. In other words, soil acidity is apparently a function of base or ion exchange phenomena.

[4] Rocks are sometimes classified as acid or basic according to their silicon content. Merrill (*Rocks, Rock-Weathering and Soils*, p. 63) groups rocks containing 65 per cent or more SiO_2 as acid; those containing 55 per cent or less SiO_2 as basic, while those containing from 55 to 65 per cent are classified as intermediate.

[5] See the work of:

Gillespie, L. J., "The Reaction of Soil and Measurements of Hydrogen Ion Concentration," *Wash. Acad. Sci. Jour.*, pp. 7-16. 1916.

Sharp, L. T., and Hoagland, D. R., "Acidity and Absorption in Soils as Measured by the Hydrogen Electrode," *Jour. Agric. Resch.*, 7, pp. 123-145, 1916.

Truog, E., "Soil Acidity. I. Relation to Growth of Plants," *Soil Science, 5*, pp. 169-195. 1918.

Plummer, J. K., "Studies in Soil Reaction as Indicated by the Hydrogen Electrode," *Jour. Agric. Resch., 12*, pp. 19-31. 1918.

Hoagland, D. R., and Sharp, L. T., "Relation of Carbon Dioxide to Soil Reaction as Measured by the Hydrogen Electrode," *Jour. Agric. Resch., 12*, pp. 139-148. 1918.

[6] Page, H. J., "The Nature of Soil Acidity," *Trans. of the Second Commission of the Internat. Soc. of Soil Sci.*, Gröningen (Holland), Vol. A, pp. 232-244. 1926.

[7] Kelley, W. P., and Brown, S. M., "Ion Exchange in Relation to Soil Acidity," *Soil Science, 21*, pp. 289-302. 1926.

[8] In the pH scale, the distance between the several points is a degree of dilution. For each point in a decreasing pH the dilution is increased 10 times over the proceeding point. For example, assuming that a hydrochloric acid solution is 100 per cent ionized, then its normality may be considered

In view of the fact that the problem of soil acidity has such great practical importance many qualitative tests [9] for its determination have been proposed. These tests make little or no attempt to determine the kind or condition of acidity but confine their attention to a measure, by various methods, of the approximate amount of lime required for maximum productivity.

Soil reaction is apparently closely connected with the dynamic functions of the mass. As these are continually changing it would be natural to suppose that the reaction would vary. The literature, however, is strangely silent regarding systematic observations of the dynamics of soil reaction. It is quite possible, however, that such changes would occur and may be quite marked. Hemmerling [10] presents (Fig. 20) a cartogram of the actual reaction of a virgin podzolized soil at four periods, extending over fourteen months. The size of the area was two hectares (approximately five acres). It will be noted that the moisture content of the area in 1924 was markedly increased between the two periods, also that the temperature of both October periods

as identical with its hydrogen ion concentration, we would then have the following series:

Normality	pH	(H^+)	(OH^-)
N/1 Hcl	0.0	1.0	10^{-14}
0.1 "	1.0	10^{-1}	10^{-13}
0.01 "	2.0	10^{-2}	10^{-12}
. . .	. .	. .	. .
0.000001 Hcl	6.0	10^{-6}	10^{-8}
Neutral	7.0	10^{-7}	10^{-7}

Or, expressing the relationship as the amount of acid required to change the pH of a non-buffered solution we would have the following scale:

Cubic Centimeters of N/1 HCl		Cubic Centimeters Pure Water, pH 7.0		pH of Resultant Solution
100.0	+	900.0	=	1.0
10.0	+	990.0	=	2.0
. .	.	. .	.	.
0.001	+	999.999	=	6.0

In other words the addition of one drop of N/1 acid (100% ionized) to a liter of pure water would change the pH from 7.0 to approximately 4.0. One cubic centimeter would change it to 3.0, while the addition of 99 cc. more would be required to reduce the pH from 3.0 to 1.0.

[9] In addition to the methods reviewed in the citations given above, see:

Stephenson, R. E., "Soil Acidity Methods," *Soil Science*, *6*, pp. 33-52. 1918.

Harper, H. J., and Jacobson, H. G. M., "A Comparison of Several Qualitative Methods for Soil Acidity," *Soil Science*, *18*, pp. 75-84. 1924.

Emerson, Paul, *Soil Characteristics*. McGraw-Hill Book Co. New York. 1925. 219 pp.

[10] Hemmerling, V. V., *Russian Investigations Concerning the Dynamics of Natural Soils*. Published by the U. S. S. R. Academy of Sciences. Leningrad 1927. 20 pp.

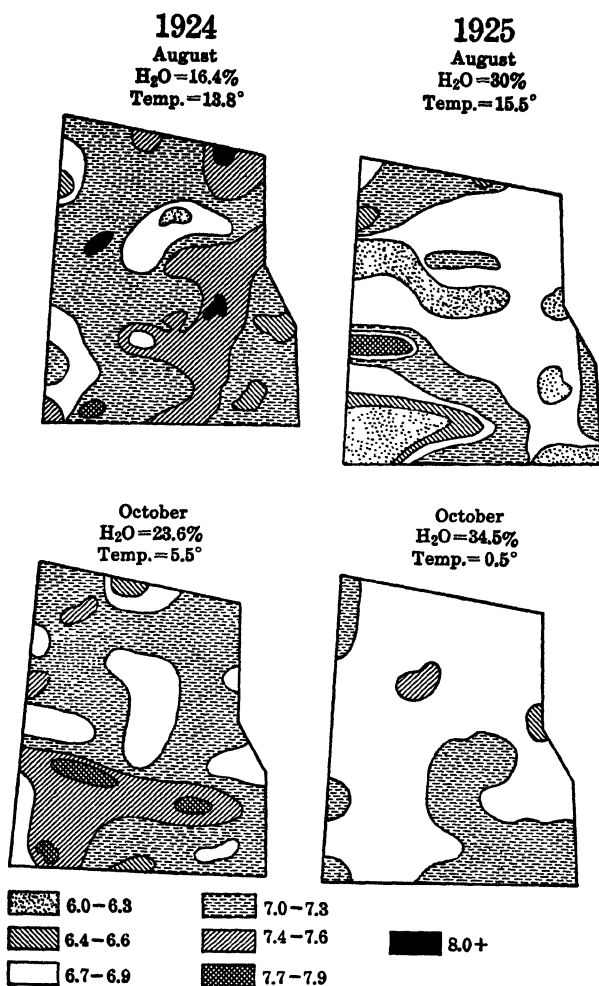



Fig. 20.—Reaction of a Russian soil at different periods.

was much lower than the August periods. Conner [11] studied soils under saturated, half-saturated, quarter-saturated, and air-dry conditions, and found that the acidity of the soil mass varied with the amount of moisture. Usually the soil kept in a half-saturated condition showed an increase in initial acidity. If,

[11] Conner, S. D., "Soil Acidity as Affected by Moisture Conditions of the Soil," *Jour. Agric. Resch.*, *15*, pp. 321-329. 1918.

however, the soils were air dried there was a variation—sometimes a gain, sometimes a loss of acidity. The results indicate that the base-exchange properties of the soil mass are also affected by the moisture content. A potassium nitrate extraction of soils kept under saturated conditions contained much larger amounts of iron and manganese and usually less amounts of aluminum than soils kept under lower moisture contents. When the soil mass was dried and extracted with potassium nitrate it was found that the solubility of the iron was decreased, the solubility of the manganese unchanged, and the solubility of the aluminum varied.

217. Alkalinity.—When rock masses are finely ground and placed in water,[12] the solution usually shows an alkaline reaction to phenolphthalein. The residual effect of rock decomposition, that is, the soil mass, usually will not give this reaction. Soils, however, are developed under different climatic conditions, one of which is a marked variation in the amounts of rainfall. Where the rainfall is abundant there is a tendency to leach out a portion of the various salts formed in the process of rock decomposition. Where the rainfall is insufficient these salts tend to accumulate in the various horizons. As these salts are soluble, capable of being transported by water, they may move as the water moves. The water, however, evaporates from the surface of the soil, leaves the salts behind, and thus may cause a concentration in the upper horizons. This concentration may be to such an extent as to render ordinary vegetative growth impossible.

Soil alkalinity is not alkalinity in a strictly chemical sense; rather it is a condition brought about by the presence of any salt or combination of salts occurring in quantities sufficient to injure, retard, or inhibit crop growth. The word "alkali" is only one of the many names applied to soluble salts. A soil may be calcareous, saline, or alkaline. The term alkalinity is justified, however, as the kinds of salts usually give a basic reaction.

Generally soil alkali [13] consists of a mixture of rather simple

[12] Cushman, A. S., "The Effect of Water on Rock Powders," *U. S. Dept. of Agric. Bur. of Chemistry Bul. 92.* 1905.

[13] For an extensive bibliography on soil alkali see:

McCrory, S. H., *et al.*, "A Bibliography Relating to Soil Alkalies," *U. S. Dept. of Agric. Dept. Bul. 1314.* 1925. 40 pp.

For the formation of alkali see:

Glinka, "Die Typen Des Bodenbeldungs," *op. cit.* (**61**).

Joffe, J. S., and McLean H. C., "Alkali Soil Investigations. II. Origin of

salts, one of which may predominate. The following are the most common: sodium chloride, sodium carbonate, sodium sulfate, sodium nitrate, magnesium sulfate, calcium sulfate, frequently calcium chloride, and sometimes calcium bicarbonate. These salts are all white, but sodium carbonate dissolves organic matter and gives the soil a black greasy appearance, hence this form of salt is commonly called black alkali. The nitrates usually produce a brown color and are called brown alkali, and the sulfates and chlorides are usually called white alkali.

218. "Freezing Up" of Alkali Soils.—In reclaiming alkali soils the common procedure is to remove the excess salts by leaching. As long as the soils contain relatively large amounts of salts, the water tends to percolate freely, but when the solutes are reduced, if soluble calcium is not present, the rate of percolation falls off until a point is reached where downward movement ceases, and the soil, in the words of the farmer, "freezes up,"[14] becomes puddled and unfit for cultivation. This phenomenon is due to the precipitation of colloidal aluminum hydroxide, as the alkalinity is progressively reduced below pH 9.5 to 10, and to the almost complete dispersion of the clay fraction. As the saline soil is washed, the concentration of sodium salts is reduced and alkalinity rapidly increases due to the formation of sodium hydroxide by progressive replacement and hydrolysis of the sodium zeolite.[15] The sodium hydroxide, in turn, brings soil aluminum into solution as aluminate,

$$NaAlO_2 + 2H_2 \rightleftarrows NaOH + Al(OH)_3.$$

On continued washing, the alkalinity is reduced but with the reduction of hydroxyl-ion concentration, larger amounts of aluminum hydroxide are formed. This, together with the almost

Alkali Soils; Physical Effects of Treatments," *Soil Science, 18*, pp. 13-30. 1924.

de' Sigmond, A. A. J., "Contribution to the Theory of the Origin of Alkali Soils," *Soil Science, 21*, pp. 455-479. 1926.

de' Sigmond, A. A. J., "Hungarian Alkali Soils and Methods of Their Reclamation," *Univ. of Cal.* (Berkeley, Cal.) *Spl. Pub. Cal. Agric. Expt. Sta.* 1927. 156 pp.

[14] McGeorge, W. T., Breazeale, J. F., and Burgess, P. S., "Aluminum Hydroxide and the Freezing up of Alkali Soils during Reclamation." *Science, 64*, pp. 504-505. 1926. See also *Ariz. Agric. Expt. Sta. Tech. Bul. 11.* 1927

[15] A zeolite may be defined as a hydro-silicate containing a definite base, Ca, Na, Al, etc. Clarke (*Bul. 770*, p. 420) shows their general composition. Hilgard (*Soils*, 1907 ed., p. 37) explains their absence in the soil on the basis that they are gels and not definite crystals. The tendency at present is to consider zeolites as colloids.

complete dispersion of the clay particles, at these alkalinities, renders the soil practically impervious to air and water.

219. Classification of Alkali Soils.—The phenomenon of "freezing up" does not take place in all forms of alkali soils. The reactions involved consist mainly in an exchange of base, in consequence of which important chemical and physical properties are produced. Kelley and Brown [16] divide alkali soils into three classes:

I. Soils whose replaceable Ca and Mg have been mainly substituted by Na.—This class is characterized by a high content of water-soluble Na salts, a low content of soluble Ca and Mg and usually more or less Na_2CO_3. Such soils become extremely impermeable upon leaching out of the soluble salts.

II. Soils in which the substitution of Na has taken place to a limited extent only.—These soils may also contain a high concentration of Na salts, but, if so, they also contain considerable soluble Ca. Such soils are less impervious than those of the first group.

III. Soils which do not contain abnormal amounts of replaceable Na.—This class is characterized by a relatively high concentration of Ca and Mg salts. In this case the concentration of Na salts may be extremely high without producing any considerable substitution of bases. Soils of this kind do not become impermeable upon leaching out the salts.

220. Buffer Action.—The soil mass has a strong tendency to remain more or less constant from the standpoint of reaction. Due to the fact that the acidity of the soil may be of several forms, we find that it cannot be neutralized in the same manner as a mineral acid may be neutralized by the addition of an alkaline solution. Rather there is a tendency of the hydrogen ion to be (to a certain degree) constant. The ability of the soil to resist a change of condition (that is, to regulate reaction) lies in the properties of certain constituents (the organic matter, proteins, salts of phosphates, etc., and of the colloidal particles) that are spoken of as buffers. This property of reaction regulation [17] is spoken of as buffer action.

[16] Kelley, W. P., and Brown, S. M., "Base Exchange in Relation to Alkali Soils," *Soil Science, 20*, pp. 477-495. 1925.

[17] For a discussion of the principles involved see Kolthoff, I. M., and Furman, N. H., *Indicators*, pp. 1-54. John Wiley and Sons. New York, 1926. 269 pp.

Buffer action takes place only in solutions. A buffer solution consists usually of a mixture of an acid with its alkali salt. Buffers may be defined as "substances which by their presence in solution increase the amount of acid or alkali that must be added to cause unit change in pH." The value of a buffer solution may be defined as follows: "A solution has a buffer value of 1 when a liter will take up 1 gram equivalent of strong acid or alkali per unit change in pH."

Practically all soils are buffered toward both acids and bases. As the limits of acidity and alkalinity tolerated by plants are fairly well defined (262) Charlton [18] assumes the points pH 4.5 and 9.5 as the buffering limits. The buffer action found within these limits is defined as the *total buffer capacity*. For instance, the total buffer capacity toward acid is the amount of N/1 H_2SO_4 in cubic centimeters required to bring 100 grams of soil to pH 4.5. Similarly the total buffer capacity toward alkali is the amount of N/1 $Ba(OH)_2$ in cubic centimeters required to bring 100 grams of soil to pH 9.5. The variation in unit change in pH is designated as *buffer action per 1.0 pH* toward acid or toward base. Pierre [19] proposes the terms "total" and "specific buffer capacity," the latter term being confined to values obtained in comparing soils of approximately the same pH.

Total buffer capacity toward acid = cc. of N/1 H_2SO_4 per 100 grams of soil to change soil to pH 4.8.

TABLE 33

BUFFER CAPACITY OF SOME SOIL TYPES

SOIL TYPE	LOCATION	H-ION	BUFFER CAPACITY TO pH 4.8	
			Specific	Total
Norfolk sand	Alabama	5.65	0.35	0.30
Cecil sandy loam	South Carolina	5.90	1.45	1.60
Tifton sandy loam	Georgia	5.80	0.94	0.94
Lintonia silt loam	Arkansas	6.20	1.00	1.40
Colby silt loam	Wisconsin	5.60	1.60	1.28
Hagerstown silt loam ...	Pennsylvania	5.60	1.50	1.20
Yolo silty clay loam ...	California	7.00	5.32	11.70

[18] Charlton, J., "The Buffer Action of Some Burma Soils," *Mem. Dept. Agric. India* (Chem. Ser.) 7, p. 101. 1924.

[19] Pierre, W. H., "Buffer Capacity of Soils and Its Relation to the Development of Soil Acidity from the Use of Ammonium Sulfate," *Jour. Amer. Soc. Agron.*, *19*, pp. 332-351. 1927.

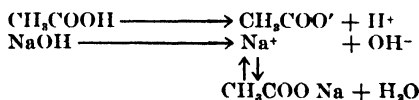
$$\text{Specific buffer capacity toward acid} = \frac{\text{total buffer capacity toward acid,}}{X - 4.8}$$

where X is the original pH of the soil. The buffering capacity of some soils is shown in Table 33.

The buffer action of soils,[20] as commonly understood, is concerned mainly with the exchange complex and is an expression of the replacing activity of H ions. When the H-ion concentration of a solution, brought into contact with a given soil, exceeds that given by the ionization of the exchange complex, an exchange of ions will take place. This results in H ions being absorbed from the solution and the formation of a simple salt of the substituted base or bases. The buffer property against acids is thus conditioned on the presence of a base or bases in replaceable form. The extent of the effect is determined by the amount of bases present. Its value in soils determination is that it may serve as an index of the rapidity (efficiency) of various materials (lime, fertilizer, etc.), in effecting changes in soil reaction.

Oden [21] states, "When a soil or soil suspension is treated with acids or alkalies generally, one of three processes will dominate. At higher concentrations the coagulation effect will dominate and it will depend on the degree of agitation how far we proceed toward the chemical equilibrium. At very low concentration all added H ions will be taken up and the neutralization of some of the ('alkalineoid') particles will be the chief movement. At intermediate concentrations all the processes may be interfering with another."

[20] Buffer action may be illustrated by the changes taking place in an acetic acid solution being neutralized by the addition of a sodium hydroxide solution. The ionization of the two solutions is as follows:

$$\begin{array}{lll} CH_3COOH \longrightarrow & CH_3COO' & + H^+ \\ NaOH \longrightarrow & Na^+ & + OH^- \\ & \uparrow\downarrow & \\ & CH_3COO\,Na + H_2O & \end{array}$$

The action takes place in three stages as follows:

1. The addition of a small amount of hydroxide at first causes an increase of the sodium ion and a rapid neutralization and depression of the H ion.
2. As the sodium acetate forms in increasing amounts it causes a depression of the ionization of the salt. Buffer action. Hence the addition of a certain amount of the alkali causes no change in the H-ion concentration.
3. Gradually less and less of the acid remains and there is a smaller and smaller amount of ionization. As the salt forms in larger amounts it begins to hydrolize, causing a more or less quick increase of the OH ion.

[21] Odén, Sven, "Discussion on Soil Acidity," *ibid.*, p. 27.

CHAPTER 18

ORGANIC MATTER

The accumulation of plant and animal remains, containing all the elements assimilated by plants, may be grouped under the heading of "organic matter." The mineral elements in this organic matter play rather a small chemical rôle in the soil. They are mainly concerned with the micro-biological functions. The elements carbon and nitrogen play a very important rôle. Not only are they concerned with the micro-biological functions but they are intimately concerned with the physical and chemical functions. This is particularly true of the element carbon.

221. Source of Organic Matter.—Plant and animal remains consist mainly of water, carbon, and nitrogen combined with relatively small amounts of minerals. The water and mineral elements are derived almost entirely from the soil; in fact, the soil has always been the original source of supply for these materials. In the case of carbon and nitrogen the source is somewhat different. Both of these elements originally came from the air. Both have been added to the soil. But they differ in their influence on higher plants in the fact that carbon can only be assimilated from the air and nitrogen from the soil. This relationship does not hold in the case of the micro-biological soil life. Further, plants utilize large amounts of carbon and only comparatively small amounts of nitrogen.

The amount of carbon and nitrogen in the atmosphere is in opposite order to their requirement by plants. Hopkins[1] estimates that there is less than 10,000 pounds of carbon in the air above one acre of land. In other words, there is only enough carbon in the air to supply the needs of two 100-bushel crops of corn. Of course the carbon of the air is equally distributed over land and water. When we consider that approximately three-fourths of the earth's surface is water, and that the above crops

[1] Hopkins, C. G., *Soil Fertility and Permanent Agriculture*, pp. 33-36. Ginn and Company, New York, 1910, 653 pp.

are decidedly above the average, the available carbon supply becomes extended over a much longer period.

On the other hand, the amount of nitrogen over each acre is enormous. A column of air one inch square and to the height of the atmosphere weighs approximately 15 pounds, equivalent to 2160 pounds per square foot, or less than 95 million pounds per acre. Approximately three-quarters of this is nitrogen—a supply, if available, to meet the nitrogen needs of crops for thousands of years. Yet the element carbon has no value as a plant food, while the element nitrogen commands a rather high price in the markets.

222. The Decomposition of Organic Matter.—When plant or animal remains are added to the soil, some of the constituents tend to undergo rapid decomposition. This decomposition process is the result of the microscopic biological population of the soil, which utilizes the material as food. The nature of the process depends on the physical and chemical conditions of the soil and the adaptability of the population to function under these conditions. The rapidity of decomposition depends on the nature of the organic matter, on the kinds of organisms active in the process and on the influence of their environmental conditions. From the standpoint of rapidity of decomposition, organic matter may be divided into two classes, active and inactive, although no sharp line may be drawn between them. The process of decomposition can best be followed by measuring the most consistent of the final products, namely, the evolution of carbon dioxide. Usually the amount of carbon dioxide produced increases until a maximum production is reached, then it begins to diminish until a certain condition of equilibrium is established. That is, the amount produced may be limited but will be fairly constant. In other words, a state is reached where the active portion has been decomposed and the inactive is being attacked by microorganisms.

The amount of carbon dioxide liberated will not account for all of the carbon added to the soil in the form of organic matter. A variable portion of the addition will persist in the soil mass and tend to become, to a certain extent, an integral constituent of the mass. This state is only reached when the readily decomposable constituents have disappeared and only the most resistant constituents remain. The less easily decomposable remains,

together with certain products formed in the earlier stages of decomposition, undergo a slow transformation with the result that a limited but constant amount of carbon dioxide is being liberated.

223. The Form of Soil Organic Matter.[2]—Plant and animal remains when first added to the soil are relatively insoluble. This material forms the food of the micro-biological soil population. In order to assimilate this food the organisms must reduce it to a soluble state. This is accomplished by various processes **(332)**. The material soon loses its original cell structure, becomes soft, spongy, highly absorbent, and finally reaches a stage of homogeneity that gives no indication of its original form. In other words, the original structure of organic matter is being subdivided into smaller and smaller aggregates, approaching and entering into the stages of the gel, the colloidal suspension, the colloidal solution, and the molecular soution **(102)**. All of these stages may be and usually are present in the soil mass.

224. The Composition of Soil Organic Matter.—It appears that soil organic matter may be divided into four distinct groups of substances, some of which possess well-defined chemical characteristics.

I. Substances Insoluble in Dilute Alkaline Solutions.—These substances are insoluble even after prolonged extraction, either in the cold or at 100° C. This fraction of soil organic matter contains the so-called "humus coal" or substances of a high carbon and low oxygen and nitrogen content. This fraction is referred to in older literature as "humin" or "ulmin."

II. Substances Soluble in Dilute Alkali Solutions.—(The concentration is usually 1.5 to 5 per cent NaOH) in the cold or

[2] For a résumé and summary of the literature on soil organic matter see: Waksman, S. A., "The Origin and Nature of the Soil Organic Matter or Soil 'Humus'."

I. "Introductory and Historical," *Soil Sci.*, *22*, pp. 123-162. 1926.

II. "Methods of Determining Humus in the Soil," *ibid.*, *22*, pp. 221-232. 1926.

III. "The Nature of the Substances Contributing to the Formation of Humus," *ibid.*, *22*, pp. 323-333. 1926.

IV. "The Decomposition of the Various Ingredients of Straw and of Alfalfa Meal by Mixed and Pure Cultures of Microörganisms," *ibid.*, *22*, pp. 395-406. 1926.

V. "The Rôle of Micro-Organisms in the Formation of Humus in the Soil," *ibid.*, *22*, pp. 421-436. 1926.

See also Symposium on "Soil Organic Matter," *Jour. Amer. Soc. Agron.*, *19*, No. 5, 1927.

under pressure and precipitated with hydrochloric acid. Characterized by a definite nitrogen content, usually 2 to 4 per cent, lower in the case of peat, and a low ash, about 1 per cent. Comprises the so-called "humic acids" (alpha fraction).

III. Soluble As in II but Precipitated by Hydrochloric Acid at a Definite Isoelectric Zone (Ph 4.6 to 5.0).—Characteristic of mineral soils. The carbon: nitrogen ratio is about the same as the alpha fraction but the ash consists almost entirely of aluminum. Probably an aluminum-organic compound. Comprises the so-called "humic acids" (beta fraction).

IV. Substances Made Water Soluble as a Result of the Alkali Treatment.—These substances are the so-called "crenic," "apocrenic," or "fulvic" acids.

It seems that up to the present time we have no definite systematic knowledge of the true nature of soil organic matter. The work of Shreiner and Shorey [3] shows that it is not a single compound, such as humic acid, or a single group of compounds, but is composed of many different and unrelated substances. It contains at least 20 different compounds belonging to 9 chemical groups. Among other substances they isolated from their acid filtrate (corresponding to the so-called crenic and apocrenic acids) dihydroxystearic acid, picoline carboxylic acid, xanthine, hypoxanthine, cytosine, histidine, arginine, and pentosan. From the precipitate obtained from the acidified alkaline extract (corresponding to the humic and ulmic acids) they obtained resin acids, resin esters, glycerides, paraffinic acid, ligniceric acid, agroceric acid, agrosterol, and phytosterol. On the other hand Oden [4] claims that soil organic matter is made up of a few definite chemical compounds that may be classified on the basis of their solubility in alkalies, water, and alcohol, into humin, humic acid, ulmic and hymetomelanic acids, and fulvic acid. The last four are considered as successive stages in the decomposition of humin. The humic acid group appears to give true salts with alkalies (hence are true acids), but with metals other than alkalies they form insoluble colloids.

225. Humus.—When the stage of decomposition reaches an approximate equilibrium, the residual, slowly decomposable or-

[3] Shreiner, O., and Shorey, E. C., "Chemical Nature of Soil Organic Matter," *U. S. Dept. of Agric. Bureau of Soils Bul. 74*, 1910.

[4] Odén, S., "Application of Physico-chemical Methods to the Study of Humus," *Trans. Faraday Society*, *17*, pp. 288-294. 1922.

ganic matter is spoken of as "humus." Just what humus is and how it originates in the soil is largely a matter of conjecture. In fact there is a complete lack of uniformity concerning the use of the term. Some investigators (largely European) use the term to designate the total organic matter content of the soil. Some (largely American) apply the term to that portion of the organic matter soluble in alkalics, and some limit the term to that part of the alkaline extract which is precipitated by acids. The situation is still further complicated by the lack of a standardized method for its determination,[5] and by the use of a number of terms defining more or less completely the nature of the material. Due to the fact that sugars, hemicelluloses, and celluloses of plants are readily decomposed by the biological soil population, but the lignin content of the tissues is only slowly decomposed, hence tend to accumulate, it is assumed that this material contributes to the formation of humus.[6]

Page [7] states, "The term *humus*, in its strictest chemical sense, is now applied only to that part of the dark organic colloid which can be extracted by the action of dilute alkalies and reprecipitated by acidification, while that part which is not dissolved by alkali is known as humin."

226. Chemical Effects of Organic Matter.—Dry organic matter has no chemical effect on the soil, but wet decomposing material exerts possibly the main chemical soil function. It is the main source of carbon dioxide, consequently may be regarded as the main factor in carbonization **(207)**. This effect continues throughout the active stages of decomposition but does not cease entirely as long as organic matter is present in the soil mass. The organic matter content of the soil mass is intimately associated with the physical, physico-chemical, chemical, bio-chemical, and biological soil functions. The chemical effects are grouped by Salter [8] as follows:

[5] The quantitative determination may be based upon:
1. The total carbon times the factor 1.74.
2. The oxidation of the organic matter with hydrogen peroxide, potassium permanganate, silver chromate, etc.
3. Extraction with various solvents, usually dilute alkalies.

[6] Beckley, V. A., "The Formation of Humus," *Jour. Agric. Sci.*, *11*, pp. 69-77. 1921.

[7] Page, H. S., "The Part Played by Organic Matter in the Soil System," *Trans. Faraday Soc.*, *17*, pp. 272-287. 1922.

[8] Salter, F. J., "The Chemical Composition of Soil Organic Matter as Related to Its Effectiveness," *Jour. Amer. Soc. Agron.*, *19*, pp. 397-409. 1927.

I. On the Solubility of Inorganic Constituents.—It appears that the solubility of calcium, magnesium, iron, etc., are measurably increased by the action of organic matter. The increased solubility is due in part to the solubility of the organic compounds resulting from decomposition and in part to the action of inorganic salts contained in the organic material. Apparently organic matter has the effect of dissolving a small amount of sesquioxides and to a lesser extent silica, the total amounting to only 2 to 3 per cent of the original weight of the soil.[9]

II. On Soil Reaction.—"For many years it was thought that soil acidity was due to the presence of complex organic acids of the nature of humic and ulmic acids." Baumann and Gully endeavored to show that this point has been the subject of extended discussion, centering mainly about the question as to whether or not the organic acids, which are formed at various stages during decomposition, persist in the soil mass. There is no question regarding the activity of such acids in increasing the solubility of the bases. Consequently the inference may be drawn that decomposing organic matter has an indirect effect in increasing the acid condition of the mass.

III. On the Absorptive Power.—It is known that the absorptive and exchange powers of the soil complex are vested in the colloidal matter. Sooner or later all organic matter assumes the colloidal state. Naturally it assumes all the properties and functions of colloids. It appears, however, that the properties of organic colloids are more marked than the properties of inorganic colloids.

IV. On the Supply of Available Nitrogen and Mineral Nutrients.—The physical, chemical, and biological effects of organic matter in relation to plant growth may be supplemented by the direct nutritional value of the material. "Averages of analyses of mineral soils show that of the total amount in soils approximately 95% of the nitrogen, 33% of the phosphorus, and appreciable amounts of the potassium, sulfur, and calcium are contained in the organic matter. In the usual fertile soils these amounts may be of sufficient magnitude to be of considerable consequence. In addition, a definite portion of the organic nutrients will be utilized by micro-organisms in the soil in the process

[9] See "Report, Sub-committee Agricultural Education Association," *Jour. Agric. Science, 16*, pp. 123-144. 1926.

of decomposition and this amount will only become available as their bodies undergo decay."

V. On the Carbon-Nitrogen Ratio.—"A study of the composition of soils soon reveals that there is a more or less constant relationship between the percentage of carbon and that of nitrogen. It seems that the amounts of these elements tend to stabilize at a proportion of 10 parts of carbon to 1 of nitrogen. Just why it is that an application of organic substances of carbon-nitrogen ratio as high as 80 to 1 results in such a narrow ratio has been the cause of considerable study." When highly carbonaceous materials are added to the soil, the biological activities cause a loss of carbon, or if a highly nitrogenous material is added there may be a loss, by the same agencies, of nitrogen. In other words, there is an effort on the part of nature to keep the relationship of carbon and nitrogen content of the soil organic matter at a stable ratio. The carbon-nitrogen ratio of the original material markedly affects its decomposition rate. Materials of narrow ratio (dried blood, etc.) decompose at a faster rate than materials of a wide ratio (woody materials).

VI. On the Reduction of Nitrates.—If a material of high carbon but low nitrogen content is added to the soil, it not only decomposes slowly but in decomposing it the micro-organisms, of necessity, must utilize the available nitrogen in the surrounding soil medium [10] for their metabolic functions. The assimilation of nitrates by the micro-organisms causes a depressed plant growth,[11] which may be overcome by the addition of a nitrogen-containing salt.

VII. On the Presence of Toxic Compounds.—In 1909, the work of Schreiner and Shorey [12] seemed to prove that infertile soils contained organic compounds injurious to plant growth. This work formed the basis for the widely known Bureau of Soils toxic theory of plant growth. The injurious effects were decreased by the addition of fertilizers [13] or by improving the physical and

[10] Wilson, B. D., and Wilson, J. K., "An Explanation for the Relative Effects of Timothy and Clover Residues in the Soil on Nitrate Depression," *Cornell Univ.* (New York) *Agric. Expt. Sta. Mem. 95.* 1925.

[11] Martin, T. L., "Effect of Straw on the Accumulation of Nitrates and Crop Growth," *Soil Science, 20,* pp. 159-164. 1925.

[12] Schreiner, O., and Shorey, F. C., "The Isolation of Harmful Organic Substances from Soils," *U. S. Dept. of Agric. Bur. of Soils Bul. 53.* 1909.

[13] Schreiner, O., and Skinner, J. J., "Organic Compounds and Fertilizer Action," *U. S. Dept. of Agric. Bur. of Soils Bul. 77.* 1911.

chemical condition[14] of the soil (drainage, liming, tillage, etc.). For a long time workers have been skeptical of this theory but the work of Collison and Conn[15] seems to prove that large amounts of decomposing organic matter do contain such toxic substances as salicylic acid, dihydroxystearic acid, or vanillin.[16]

VIII. On Growth-promoting Accessory Substances.—"The fact that the composition of soil organic matter might include some growth-promoting accessory substance, analogous to vitamines for animals, was brought into prominence by Bottomley[17] in England. He found that extracts from bacterized peats had a remarkable effect on the growth of some plants both in water cultures and in soils. He attributed this effect to the presence of some accessory substance which he called "auximones." In order to test the actual existence of such substances, Bottomley worked with *Lemna major,* a plant reproducing by budding, in order to avoid the use of seeds, as these might bear auximones. In the soil these plants grew well, but in Detmer's and Knop's solutions they failed to grow satisfactorily unless some organic extracts were supplied. Clark[18] and Clark and Roller[19] have tested the results of Bottomley by using the same plants and solutions and find that the growth of *Lemna major* in mineral solutions depends upon the concentration of the salts and that no organic matter is needed. They conclude that auximones are not essential for

[14] Robbins, W. J., and Massey, A. B., "The Effect of Certain Environmental Conditions on the Rate of Destruction of Vanillin by a Soil Bacterium," *Soil Science, 10*, pp. 237-246. 1920.

[15] Collison, R. C., and Conn, H. J., "The Effect of Straw on Plant Growth," *N. Y. State* (Geneva) *Agri. Expt. Sta. Tech. Bul. 114.* 1925.

[16] It is interesting to note in addition to the earlier soils work on toxic compounds noted above, that another and totally independent line was under investigation at apparently the same time, namely, the question of the toxicity of bog waters. See:

Livingston, B. E., "Physical Properties of Bog Waters," *Bot. Gaz., 37*, pp. 383-385. 1904. Also, "Physiological Properties of Bog Waters," *Bot. Gaz., 29*, pp. 348-355. 1905.

Dachnowski, A., "The Toxic Properties of Bog Water and Bog Soil," *Bot. Gaz., 46*, pp. 130-143. 1908.

Rigg, G. B., "A Summary of Bog Theories," *Plant World, 10*, pp. 310-325. 1916.

[17] Bottomley, W. B., "The Growth of Lemma Plants in Mineral Solution and in Their Natural Media. The Effect of Organic Matter on the Growth of Various Water Plants in Culture Solutions," *Ann. Botany, 34*, pp. 345-352. 1920.

[18] Clark, N. A., "The Soil Organic Matter and Growth-Promoting Accessory Substances," *Jour. Ind. and Eng. Chem., 16*, pp. 249-250. 1924.

[19] Clark, N. A., and Roller, E. M., "Auximones and the Growth of the Green Plant," *Soil Science, 17*, pp. 193-198. 1924.

growth and reproduction. Auximones may, however, prove stimulating, similar to the action of bios in the reproduction of yeast.

227. Biological Effects.—The fact that organic matter is the center of soil functions and that its decomposition is a function of the biological soil population leaves no doubt of the importance of this phase of the soil. There are, however, so many factors concerned in the process that the discussion is reserved for the next section.

CHAPTER 19

THE SOIL SOLUTION

The water content of the soil mass acts as a chemical and biological agent between the soil particle and the plant. In other words, water acts (1) as a solvent of the soil-derived plant food elements, (2) as a carrier of these elements to the plant, (3) as an absorbent of the gases produced in biological processes, and (4) as a source of supply of hydrogen and oxygen used in large amounts by plants.

Soil water, like soil air, bears little relationship to pure water. Falling rain washes the atmosphere free of gases and particles **(142)** which are carried into, or deposited on, the soil. Also in entering the soil mass, water encounters and displaces the soil air. Many of the gases composing the latter are soluble in the former, consequently the solvent powers of the soil water may be markedly changed. Further the powers acquired by the water in the upper levels, "Horizon A," may be changed in the lower levels, "Horizon B," so that when water finally emerges from the soil (water table, springs, etc.), it may be again practically pure. It is evident, therefore, that the water content of the soil mass has individual characteristics, especially as a solvent and carrier of elemental materials that are of great importance in plant growth.

228. The Soluble Materials of the Earth's Surface.—It is estimated (Clarke, *Bul. 770*, p. 63) that the total annual rainfall upon all the land of the globe amounts to 29,347 cubic miles, and of this quantity 6,524 cubic miles drain off through rivers to the sea. A cubic mile of river water weighs approximately 4,205,650,000 tons and carries in solution 420,000 tons of foreign matter. In other words, nearly three billion tons of soluble materials are removed from the surface of the land annually, as practically one-half of the land surface is under arid conditions, the amount of solubles (most of which are plant food materials) removed by water is enormous **(241, 242)**. This process going

on for ages has produced: (1) A tendency for a concentration of salts in the various bodies of water draining the land. The concentration may or may not persist. (2) The concentration of salts left by the evaporation of water has given rise to various salt deposits (limestone formations, gypsum, potassium, sodium, etc.) that may have an agricultural value when returned to the soil. (3) The salts serve as a basis for biological soil-forming activities, thus resulting in the possible formation of new soil areas, of deposits (phosphates, limestones, etc.) that also may have an agricultural value.

229. Solubility of Soil Minerals and Rocks as Affecting the Soil Solution.—All minerals and rocks are to a certain degree soluble; the degree, however, varies widely. This is shown by the work of Bouyoucos,[1] who studied the solubility of 52 different kinds of rocks and minerals common to the soil. He found that quartz was least and apophyllite most soluble. The solubility varied apparently in inverse proportion to the concentration of moisture in the mass; for instance, at 20 per cent moisture the concentration of quartz in solution was 350 ppm., of ferrugineous sandstone 1811 ppm., and of apophyllite 2187 ppm. When, however, the soil solution was diluted to 75 per cent of the rock or mineral mass, the concentration for quartz was 100 ppm., of ferrugineous sandstone 711 ppm., and of apophyllite 975 ppm. When the powdered materials were leached, the amount in the solution, present in the mass, was usually markedly decreased, but there was always a measurable amount of materials in solution after repeated extractions. Apparently the rate of solubility was rapid as the quantity of additional solubility over an extended period was extremely small.

230. Solubility of Soils.—In a study of the solubility of soils from Michigan, Rhode Island, New York, Ohio, and Illinois, Bouyoucos [2] found that the rate of solubility is slow but gradual. The maximum quantity of material that went into solution increased from approximately 250 ppm. to 1000 ppm. in 60 days.

If, however, either rock or mineral powders or different classes

[1] Bouyoucos, G. J., "Rate and Extent of Solubility of Minerals and Rocks under Different Treatments and Conditions," *Mich. Agric. Expt. Sta. Tech. Bul. 50.* 1921.

[2] Bouyoucos, G. J., "Rate and Extent of Solubility of Soils under Different Treatments and Conditions," *Mich. Agric. Expt. Sta. Tech. Bul. 44.* 1919.

of soil were treated with solutions of salts, comonly used as fertilizers, the solubility of the less soluble portion of the mass was usually increased. In some cases the amounts increased from 125 ppm. to as much as 2750 ppm.

231. Factors Affecting Solubility of Soils.—The work of the United States Bureau of Soils [3] showed that the concentration of the soil solution depends upon many factors. Solubility was influenced by temperature, pressure, carbon dioxide, inorganic salts, organic compounds, and such vital forces as the presence of plants, micro-organisms, etc.

232. Solubility of Compounds Containing Plant-Food Elements.—The simpler compounds containing the soil-derived plant-food elements, important in or affecting plant growth, may be arranged in the decreasing order of solubility as follows:

Bases		*Acids*	
Sodium	Na	Nitrate	NO_3
Potassium	K	Chloride	Cl
Calcium	Ca	Bicarbonate	HCO_3
Magnesium	Mg	Sulfate	SO_4
Iron	Fe	Carbonate	CO_3
Aluminum	Al	Phosphate	PO_4

The above arrangement is merely illustrative. In general, it may be said that nitrates, chlorides and bicarbonates are very soluble, the sulfates of Na and K quite soluble, less so in the case of Ca and Mg, the carbonates of Na and K are very soluble, but of Ca and Mg are rather insoluble, while the phosphates are usually only slightly soluble. The solubility effects will depend markedy on reaction; for instance, the iron and aluminum compounds do not become a solubility factor until an extremely acid or alkaline condition is attained (253).

233. The Soil Solution.—The soil water imparts to the soil mass a number of physical properties. Among these are the physico-chemical properties of adsorption and absorption. Further,

[3] Whitney, M., and Cameron, F. K., "The Chemistry of the Soil as Related to Crop Production," *U. S. Dept. of Agric. Bur. of Soils Bul. 22.* 1903.

King, F. H., "Investigations in Soil Management," *U. S. Dept. of Agric. Bur. of Soils Bul. 26.* 1905.

Cameron, F. K., and Bell, J. M., "The Mineral Constituents of the Soil Solution," *U. S. Dept. of Agric. Bur. of Soils Bul. 30.* 1905.

Cameron, F. K., *The Soil Solution. The Nutrient Medium for Plant Growth.* Easton, Pa., 1911. 136 pp.

the chemical properties of the soil mass only function in the presence of water, on which plant life is absolutely dependent. It has been shown that there is a certain relationship between the soil particle and the surrounding moisture film **(211)**. The majority of the ionized particles in this film can move only a short distance away. They are only indirectly subject to physical forces, are leached very slowly, but presumably may be withdrawn by the osmotic and selective adsorption action of plant roots.

This area of soluble dissociated and undissociated materials, surrounding the solid soil particle, and from which the plant root absorbs its soil-derived elements, constitutes the soil solution. It is a true solution, as opposed to a suspension, and is the material which nourishes the plant. This solution is the chemically active soil water. It is both the solvent and the solute, consisting of gases, liquids, and solids, more or less constantly reacting with each other. It is markedly dynamic in character, in the soil mass is apparently constantly changing its composition and concentration. It is subject not only to physical and chemical functions but to the complex life-processes connected with the biological functions. It cannot, therefore, be regarded as static in character.

234. Character of the Soil Solution.—Little is known of the exact character of the soil solution. This is due, not to lack of effort on the part of soil investigators, but to the extreme difficulty of separating the moisture film from the soil particle. Many ingenious devices [4] have been used to overcome this attractive force; for instance, a centrifugal force approximately equivalent to three thousand times gravity; a press exerting a minimum pressure of 53,000 pounds per square inch; the replacement of the soil solution by means of oils, liquid organic compounds, etc., or diluting the solution with an excess of water. But all methods, especially those using force of any kind, are open to objection because the solution changes both in composition and concentration, thus giving no accurate information regarding the proportion of nutrients available for plant use. In fact, many of the solutions obtained by these methods fail to support plant growth. The solution thus obtained may, however, be adjusted to a

[4] For a review of methods see Parker, F. W., "Methods of Studying the Concentration and Composition of the Soil Solution," *Soil Science*, *12*, pp. 209-232. 1921.

physiological balance [5] by the addition of nutrient salts. A comparison of the plant growth in the supplemented and control solutions indicates the needs of the soil extract. The dilution method,[6] using water in the ratio of 5 to 1 as the solvent, shows that the soil moisture in the soil mass is practically a saturated solution of mineral substances. If, however, a greater dilution is used, 10 to 1 or above, a distinct change in the amount of nutrients extracted takes place. (See Fig. 21.) [7]

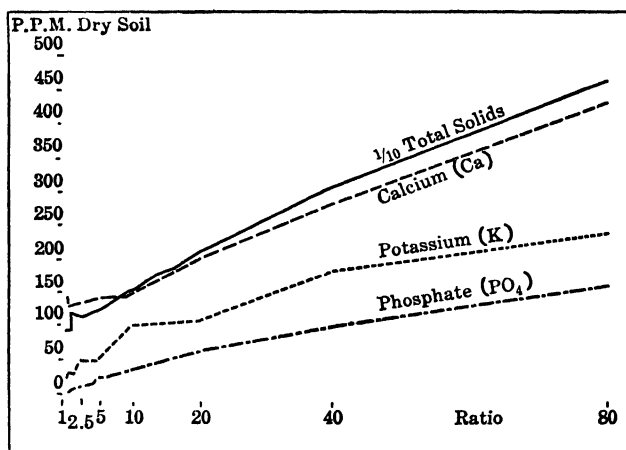



Fig. 21.—Nutrients extracted from Yolo silty clay loam by varying the ratio of soil to water.

It appears that striking differences may occur between the amounts of soluble nutrients present in various uncropped soils. These differences are not so apparent when the soils are cropped. The differences are greater between nitrates, calcium, and magnesium. The phosphate content of any one soil appears to be fairly constant, but between different soils may exhibit great dissimilarity. Further, there is apparently a considerable fluctuation in the nutrient content of the soil solution from day to day. (See Fig. 22.) [7]

[5] Hibbard, R. P., "Physiological Balance in the Soil Solution," *Mich. Agric. Expt. Sta. Tech. Bul. 40*. 1917.

[6] Schreiner, O., and Failyer, G. H., "Colorimetric, Turbidity and Titration Methods Used in Soil Investigations," *U. S. Dept. of Agric. Bur. of Soils Bul. 31*. 1906.

[7] Stewart, Guy R., "Effect of Season and Crop Growth in Modifying the Soil Extract," *Jour. Agric. Resch., 12*, pp. 311-368. 1918.

The general results of an extended study of soils, conducted mainly in California and Michigan (using the ingenious freezing-point method developed by Bouyoucos and McCool [8]) in comparison with complete analyses (fusion method) and acid extraction analyses (hydrochloric acid sp.gr. 1.115 and 1 per cent

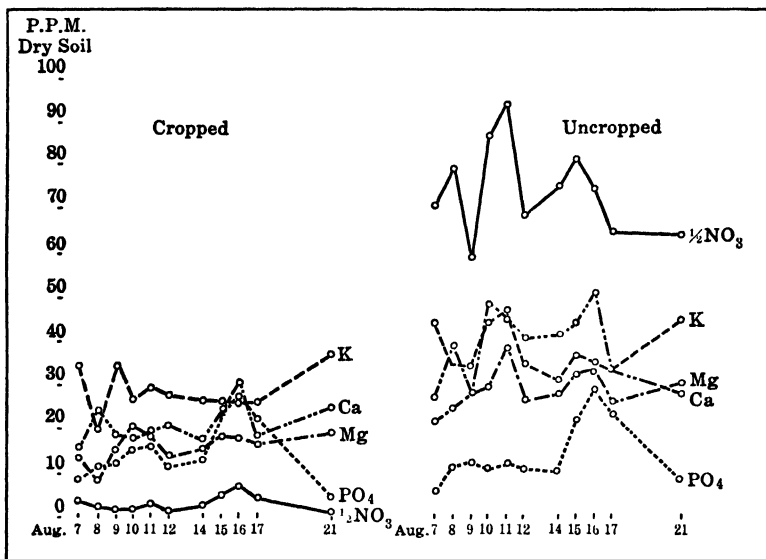



FIG. 22.—Variation in nutrients extracted (1-5 ratio) from Yolo silty clay loam under cropped and uncropped conditions.

citric acid), warrant the general conclusion that there is a close relationship between the soil solution and the 1 to 5 water extract.[9] In fact, the large number of instances in which soils of

[8] Bouyoucos, G. J., and McCool, M. M., "The Freezing-Point Method as a New Means of Measuring the Concentration of the Soil Solution Directly in the Soil," *Mich. Agric. Expt. Sta. Tech. Bul. 24*. 1916.

[9] Burd, J. S., "Chemical Criteria, Crop Production, and Physical Classification in Two Soil Classes," *Soil Science*, 5, pp. 405-419. 1918.

For general reference, see:

Bouyoucos, G. J., and McCool, M. M., "Further Studies on the Freezing-Point Lowering of Soils," *Mich. Agric. Expt. Sta. Tech. Bul. 31*. 1916.

Bouyoucos, G. J., "Classification and Measurement of the Different Forms of Water in the Soil by Means of the Dilatometer Method," *Mich. Agric. Expt. Sta. Tech. Bul. 36*. 1917.

Burd, J. S., "Water Extractions of Soils as Criteria of Their Crop-Producing Power," *Jour. Agric. Resch.*, 12, pp. 297-309. 1918.

Hoagland, D. R., "The Freezing-Point Method as an Index of Variations

low production give low figures as compared with those obtained from soils of high production is striking.

235. Equilibrium of the Soil Solution.—The physical and chemical factors affecting the solubility of soils are continually changing. It is doubtful, therefore, whether or not a state of equilibrium is ever maintained[10] in the soil solution for any great length of time. Bouyoucos[11] shows that, in spite of the fact that the solubility of soils "attains a constancy at the end of sixty days, this constancy is not a true equilibrium. In other words, the solution is not saturated when solubility ceases. This is proven by the fact, when different proportions of soil and water are employed, that an apparent equilibrium is attained in all the ratios and yet the solubility product is not at all the same when the equilibrium is reached, and it does not become the same, no matter how long the soil and water in the different ratios are kept in contact." In a later publication, Bouyoucos[12] states, "although at room temperature, the solubility of all the rocks and minerals become practically stationary immediately, at the temperature of 53°/C. it continued to go on, even at the end of 95 days, without any apparent signs of stopping, and in some of them it progressed with increasing velocity. The material which goes into solution at the high temperature still persists when the mass is cooled to --3°/C., indicating that equilibrium, or the saturation point, was not yet attained at the high temperature at the end of 95 days."

Truog,[13] in discussing the specific injurious influence of soil

in the Soil Solution Due to Season and Crop Growth," *Jour. Agric. Resch.*, *12*, 369-395, 1918.

Burd, J. S., and Martin, J. C., "Water Displacement of Soils and the Soil Solution," *Jour. Agric. Sci. 13*, pp. 265-295. 1923.

Burd, J. S., and Martin, J. C., "Secular and Seasonal Changes in the Soil Solution," *Soil Science, 18*, pp. 151-167. 1924.

Hoagland, D. R., "Physiological Aspects of Soil Solution Investigations," *Hilgardia, 1*, pp. 227-257. 1925.

[10] It is apparent that the soil is not a mixture of more or less insoluble mineral substances. Rather, it is a complex mixture of inorganic and organic materials in various states of solubility (from the true solid to the true solution), each factor of which has a certain equilibrium. The equilibrium of the mass is (if it exists) a combination of the various factors.

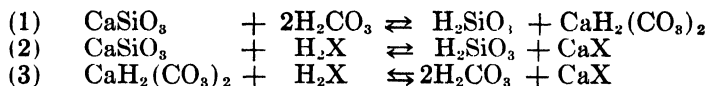
[11] Bouyoucos, G. J., "Rate and Extent of Solubility of Soils under Different Treatments and Conditions," *Mich. Agr. Expt. Sta. Tech. Bul. 44.* 1919.

[12] Bouyoucos, G. J., "Rate and Extent of Solubility of Minerals and Rocks under Different Treatments and Conditions," p. 31, *Mich. Agric. Expt. Sta. Tech. Bul. 50.* 1921.

[13] Truog, E., "The Utilization of Phosphates by Agricultural Crops, Including a New Theory Regarding the Feeding Power of Plants." *Wis. Agric. Expt. Sta. Res. Bul. 41*, 1916.

acidity on alfalfa and perhaps certain other plants, states (page 34): "When not disturbed, the soil solution comes to a state of equilibrium with the phosphates, carbonates, organic compounds, and other solid compounds. In case a soil is acid, then solid carbonates in appreciable amounts are usually absent. Hydrolysis and carbonation are the principal processes that bring dissolved mineral substances into the soil solution.

"The equilibrium conditions between the carbonic acid in the soil solution and the solid insoluble soil acids and soil silicates may be taken to illustrate the point under discussion. The insoluble soil acids of the acid soil may be represented by H_2X, and $CaSiO_3$ may be taken as a representative silicate. In the soil, there are probably present acid silicates which in this system may replace either the soil acids or silicate. In this system of soil acids, silicate and carbonic acid, the following reactions are possible:

$$(1)\quad CaSiO_3 + 2H_2CO_3 \rightleftarrows H_2SiO_3 + CaH_2(CO_3)_2$$
$$(2)\quad CaSiO_3 + H_2X \rightleftarrows H_2SiO_3 + CaX$$
$$(3)\quad CaH_2(CO_3)_2 + H_2X \leftrightarrows 2H_2CO_3 + CaX$$

"As is evident from these reactions, the concentration of calcium bicarbonate in solution at equilibrium will depend, besides the concentration of carbonic acid and temperature, upon the amount of surface exposed by the calcium silicate and especially upon the amount and strength of soil acids present causing soil acidity. If considerable amounts of relatively strong acids are present, then the concentration and rate of formation and solution of calcium bicarbonate and delivery to the plant will be too low to meet the maximum need of growing alfalfa and certain other plants, and hence the growths of these plants will be checked."

236. Solid Phases Obtained by Evaporation of the Soil Solution.—There is an extensive soils literature on the relative quantity of ions or radicals found in an analysis of the soil solution or a recalculation of these quantities as compounds supposed to be present. Previous to the publication of Anderson and Fry,[14] little was known of the actual character of the materials deposited from soil extracts upon evaporation. The study consisted of extracting large samples of soil with great quantities

[14] Anderson, M. S., and Fry, W. H., "Solid Phases Obtained by the Evaporation of Certain Soil Extracts," *Jour. Ind. and Eng. Chem.* *12*, pp. 663-669. 1920.

of water (about 400 pounds of soil extracted with sufficient water to make 1,250 liters of solution). The supernatent liquid was freed of all solid matter and concentrated in a steam kettle. At different stages in the concentration the various salts would crystallize. These crystals were removed and examined both chemically and petrographically. The petrographic examinations (see Table 34) showed the existence of complex salts in the crystalline material deposited from the extracts of both alkali and humid soils, and in addition the Yolo clay loam contained

TABLE 34

SALTS FOUND IN WATER EXTRACTS OF SOILS

(The presence of the salt is indicated by X.)

SALTS FOUND	SOIL TYPE AND ORIGIN		
	Yolo Clay Loam, White Alkali Soil Los Banos, Calif.	Chester Silt Loam Oakton, Va.	Crowley Silt Loam, Subsoil Crowley, La.
Single Salts:			
Chlorides:			
Silvite KCl	..	X	X
Halite $NaCl$	X	X	X
Sulfates:			
Gypsum $CaSO_4.2H_2O$	X	X	X
Epsomite $MgSO_4.7H_2O$	X	X	..
Kieserite $MgSO_4.H_2O$	..	X	..
Thenardite Na_2SO_4	X	X	X
Mirabilite $Na_2SO_4.10H_2O$	X	X	..
Nitrates:			
Soda niter $NaNO_3$	X	X	..
Carbonates:			
Calcite $CaCO_3$	X	X	X
Aragonite $CaCO_3$	..	..	X
Magnesite $MgCO_3$	X	..	X
Thermonatrite $Na_2CO_3.H_2O$	X	..	..
Sodium carbonate Na_2CO_3	X	..	X
Phosphates:			
Tri-sodium phosphate Na_3PO_4	X	..	..
Double Salts:			
Chlorides:			
Carnallite $KCl.MgCl_2.6H_2O$	X	X	..
Sulfates:			
Aphthitalite $(KNa)_2SO_4$	X	..	..
Picromerite $K_2SO_4.MgSO_4.6H_2O$	X	X	X
Blodite $Na_2SO_4.MgSO_4.4H_2O$	X	..	X
Loweite $2Na_2SO_4.2MgSO_4.5H_2O$	X	..	X

leonite $K_2SO_4.MgSO_4.4H_2O$; langbeinite $K_2SO_4.2MgSO_4$; vanthoffite $3Na_2SO_4.MgSO_4$; kainite $KCl.MgSO_4.3H_2O$; and the triple salt hanksite $9Na_2SO_4.2NaCO_3.KCl$.

The authors compared the solid phases of the soil solution with those obtained from sea water and saline deposits and found a marked general similarity. The latter solutions, however, contained a great many more and a greater variety of salts. As sea water and saline deposits represent a composite soil extract, it would be expected that all of these salts would be found in an exhaustive examination of the soil solution. The above results, however, are sufficient to indicate the great variety of combinations and the futility of an accurate interpretation of conditions as indicated by the ordinary soil analysis.

237. Relation of the Soil Particle to the Soil Solution.—The soil particle is entirely surrounded by the soil solution and is, to a certain degree, soluble in it. The plant apparently has the ability to remove certain ions from the soil solution. In this case, there is a direct removal and no compensating substitution. The particle (acidoid) is under stress to maintain the ionic concentration in the layer immediately surrounding it. Should it be unable to attract a compensating metallic ion from the soil solution, then it must supply (ionize) one from itself. Should it be unable to attract or supply a metallic ion, then the concentration of the layer is maintained by an H ion. In this case, the H ion acts in the same capacity as a metallic, but not necessarily, a basic, ion.

From the practical standpoint, the relation of the soil particle to the soil solution is one of supply and demand. The particle is the source of supply. The source of supply is subject to both legitimate and illegitimate demands. These demands are from sources out and beyond the soil solution. For instance, the plant may be regarded as causing a legitimate demand, while the various factors of erosion, leaching, etc., may be regarded as causing an illegitimate demand. Assuming that, throughout the ages, the particle has been enabled to reduce the illegitimate demands to a minimum consideration, we are still faced with the fact that the removal of the plant or its products causes a direct removal of soil-derived plant food elements. This removal must be compensated for in the solution. As the removal of basic is in excess of acidic ions, there is a tendency for a substitution of H

ions, which results, if there are no compensating factors, in a gradual development of acidity (216). This gradual development of acidity is important, because it usually means that at the same time there is a gradual depletion of the available soil-derived plant food elements (232), and this in spite of the fact that their presence may be shown by a chemical analysis (199). Usually the condition results in lowered productivity.

238. The Relation of Organic Matter to the Soil Solution.—The organic matter content of the soil bears the same relationship to the soil solution as the soil particle (211). In addition, it is more flexible in that it is more subject to the rapid changes induced by decomposition, mainly by biological processes. The organic matter, however, possesses all the properties of the colloid, hence is able to absorb and retain the plant food elements against the processes of illegitimate removal. Its properties in this respect are apparently far greater than that of the mineral particles. Hissink [15] shows that the organic matter content of the soil is capable of absorbing, thus increasing the base exchange (214) capacity of the soil, over five times the amount of calcium as the mineral soil.

While the organic matter content of the soil bears the same relationship to the soil solution as the mineral particle, it must not be assumed that it acts in a similar manner. The mineral particle is subject to solvent action at a very slow rate. The organic matter, on the other hand, may be subject to solvent action at a very rapid rate. The solvent action in the case of the mineral particle is due almost entirely to chemical functions. The solvent action in the case of the organic matter is due almost entirely to biological functions. The products produced in either case have a marked influence on the different solubility rates and functions.

239. Soil-Derived Plant Food Elements in the Soil Solution.—Practically all soils contain varying amounts of each of the soil-derived elements essential or necessary for plant growth. These elements occur in varying combinations (236), in varying degrees of availability, and in varying amounts (see Table 30,

[15] Hissink, D. J., "The Relation between the Values pH, V, and S (Humus) of Some Humus Soils. S (Humus) and V of Those Soils with pH = 7.0 the Equivalent Weight of the Humus Substance," *Trans. Second Commission of the International Society of Soil Science.* Gröningen (Holland), Vol. A, pp. 198-204. 1926.

TABLE 35

Removals from Lysimeters by Crop and Drainage during Five Years

Results Expressed as Pounds per Acre, Annual Average

Tank*	Phosphorus A	Phosphorus B	Sulfur A	Sulfur B	Sodium A	Sodium B	Potassium A	Potassium B	Magnesium A	Magnesium B	Calcium A	Calcium B	Nitrogen A	Nitrogen B
Dunkirk Clay Loam														
3	only a trace	20.6	31.8	11.4	99.9	9.9	52.7	90.9	30.2	8.3	2[illegible]0.7	13.0	7.3	81.0
4		...	44.0	...	122.4	...	73.3	...	60.0	..	370.8	...	102.7	...
5		21.0	31.5	10.5	68.0	8.3	39.7	90.5	28.0	8.9	104.6	16.0	5.1	81.0
6		12.8	43.2	9.4	82.5	10.4	46.5	58.7	43.1	5.1	226.0	9.8	3.2	59.6
7		20.0	43.9	11.0	70.2	7.5	43.7	83.5	40.5	8.0	167.8	12.4	4.5	73.0
8		...	53.1	...	82.9	...	48.8	...	70.4	..	364.0	...	75.0	...
9		20.8	41.0	9.3	78.8	7.5	45.9	91.1	42.9	7.8	183.6	17.6	5.6	82.6
10		12.9	37.7	9.2	71.3	10.8	46.8	57.8	37.2	4.6	1[illegible]13	9.6	3.1	57.8
11		17.0	56.4	8.8	84.1	6.5	43.7	77.5	49.2	5.8	213.1	10.2	5.3	68.4
12		19.2	62.0	10.0	79.8	6.3	40.3	84.0	37.1	6.4	1[illegible]9.7	11.5	6.8	73.8
Volusia Silt Loam														
13		9.4	35.2	9.6	...	...	88.6	35.1	2[illegible].6	[illegible]1	257.6	7.5	8.7	34.5
14		...	43.3	...	...	...	99.1	...	39.3	..	319.4	...	46.0	...
15		11.1	33.7	10.7	...	...	57.8	33.1	31.7	3.9	2[illegible]5.1	10.1	26.6	43.4
16		...	39.0	...	...	...	69.9	...	51.6	..	383.4	...	58.0	...

Column A—Removal by Drainage Column B — Removal by Crops

* Cropping system: tanks 4, 8, 14 and 16 fallow; tanks 3, 7, 11, and 12 rotated to corn, oats, wheat, and timothy (two years); tanks 5 and 9, corn, oats, wheat, timothy, and clover (two years); tanks 6 and 10, oats followed by grasses (four years); 13 and 15, oats, cowpeas, corn, oats, and barley.

Treatments: tanks 3, 4, 5, 6, 13, and 14, manure, ten tons each fourth year; tanks 7, 8, 9, 10, 15, and 16, manure plus one and one-half tons of burned lime (lime applied at beginning of experiment only); tank 11, manure plus potassium sulfate (K_2SO_4 applied 200 lbs. per acre, annually); tank 12 same as 11 but including lime.

p. 177). Let us consider the varying amounts and condition of these elements and the factors affecting their solubility.

240. Losses of Plant Food Elements.—The plant food elements may be lost or removed from the soil in four ways: (1) by the growing plant, a source of great loss if the crop is removed; (2) by volatilization, a factor of minor importance and concerned chiefly with the biological process of denitrification **(297)**; (3) by mechanical erosion, surface run-off **(242)** wind action and the various processes connected with denudation **(18)**; and (4) by leaching, *i.e.* by the action of percolating waters in carrying away the soluble materials. The extent of removal by crops has been measured (plant analysis) by practically every station, in all parts of the world, conducting soil investigations. The extent of removal by mechanical erosion and by leaching of the soil has received less attention, due possibly to the mechanical difficulties involved. The question of leaching is directly concerned with the soil solution and has been studied more or less extensively by a number of the experiment stations in the United States. Possibly the most elaborate and conclusive study of soil leaching is that conducted by Lyon and Bizzell,[16] who determined the plant food constituents removed from two types of soil, placed in lysimeters, under different cropping conditions for a five-year period.

241. Lysimeters at Ithaca, N. Y.—The lysimeters were built of concrete and lined with a coating of asphaltum to prevent the soil water from taking up any elements from the retaining walls. Each pit was 4 feet 2 inches square with a funnel-shaped bottom to which was attached a drain. The bottom was filled with sand. The tanks were filled with soil in one-foot layers arranged in the order in which they were present in the field. Tanks 1 to 12 inclusive were filled with Dunkirk clay loam and tanks 13 to 16 inclusive were filled with Volusia silt loam. The main tabular points of the experiment are presented in Table 35.

Fraps[17] shows (Table 36) the results of a three-year experiment on the percolation of water and mineral matter through

[16] Lyon, T. L., and Bizzell, J. A., "Lysimeter Experiments. Records for Tanks 1 to 12 during the Years 1910 to 1914 Inclusive," *N. Y. (Ithaca) Agric. Expt. Sta. Memoir 12.* 1918.

Lyon, T. L., and Bizzell, J. A., "Lysimeter Experiments, Records for Tanks 13 to 16 during the Years 1913 to 1917 Inclusive," *ibid., Memoir 41.* 1921.

[17] Fraps, G. S., "Losses of Moisture and Plant Food by Percolation," *Texas Agric. Expt. Sta. Bul. 171.* 1914.

TABLE 36

LOSSES OF PLANT-FOOD ELEMENTS FROM TEXAS SOILS

(Expressed as Pounds per Acre)

TYPES OF SOIL	NITRIC N.	POTASH	LIME	MAGNESIA
Norfolk sand	26.7	9.7	70.4	13.0
Orangeburg F. sandy loam	81.9	32.1	181.0	26.8
Miller F. sandy loam	85.5	39.0	259.0	49.2
Lufkin sandy loam	75.6	58.6	172.0	52.7
Huston loam	78.9	18.5	258.1	46.8
Huston black clay	147.0	8.2	441.7	40.5
Yazoo clay	244.2	66.6	582.0	51.1
Crawford clay	203.1	38.6	569.0	43.3

eight types of Texas soils, none of which were acid in reaction. The experiment was conducted in 12-inch pots and under Texas conditions.

242. Losses of Plant-Food Elements by Surface Run-Off.—It is a well-known fact that soluble salts tend to congregate at the surface of the soil. Plants also may exude large amounts of salts from the surface of their leaves. These salts, particularly those on the surface of the soil, are subject to loss by waters running off the surface. The loss [18] by these means may be considerable. Duley and Miller [19] found that in a one-year period, and with a rainfall of 45.2 inches, the total amount of soluble plant food elements (N, Ca, Mg, K, Na, S, and P) removed from the surface of the soil varied from 166.8 pounds per acre, in a plot cropped to wheat and clover, to 380.1 pounds lost from a plot spaded four inches deep in the spring and fallowed. Calcium and sulfur were lost in the largest amounts, potassium losses were relatively small, but in some cases amounted to considerably more than would be applied in ordinary commercial fertilizers. The losses of nitrogen, magnesium, sodium, and phosphorus were small.

243. Additions to the Soil Solution.—Water not only acts as an agency of removal from the soil mass, but also acts as a carrier of materials into that mass. It is well known that the wind carries great quantities of dust which, whether cosmic or terrestrial, form the nuclei around which drops of rain are formed.

[18] LeClerc, J. A., and Breazeale, J. F., "Plant Food Removed from Growing Plants by Rain or Dew," *U. S. Dept. of Agric. Yearbook*, pp. 389-402. 1908.

[19] Duley, F. L., and Miller, M. F., "Erosion and Surface Run-Off under Different Soil Conditions," *Mo. Agric. Expt. Sta. Resch. Bul. 63.* 1923.

When water vapor condenses to rain, it tends to dissolve the oxygen, nitrogen, and carbon dioxide content of the atmosphere itself, also to act as a solvent or carrier for other gases, vapors, solids, etc., that may be in the air. The dissolved or suspended materials are naturally carried by rain-water into the soil.

Little is known of the rôle played by the gaseous elements, nitrogen and oxygen, when dissolved in rain and brought into the soil. As a factor affecting the soil solution, their importance may be questioned. Combinations of these elements and of carbon, however, play a very important rôle. The importance of carbon compounds, particularly carbon dioxide, is difficult to determine, due to the great amounts being constantly exchanged from soil to air and vice versa. The importance of the atmosphere as a source of nitrogen is shown (by Clarke in *Bul. 770,* page 55, cited in **195**) in Table 37, giving the amounts of nitrogen in rain at different places on the earth.

TABLE 37

NITROGEN BROUGHT TO THE SURFACE OF THE EARTH BY RAIN

(Pounds per Acre per Annum)

Locality	Total Nitrogen	Locality	Total Nitrogen
Rothamsted	3.84	Gembloux, Belgium	9.20
Paris	8.93	British Guiana	3.54
Barbados	3.45	New Zealand	2.08
Kansas	3.69	Iceland	1.06
Utah	5.42	Hebrides	0.60
Mississippi	3.63		

Schutt and Hedley [20] show (Table 38) the relative annual contribution of nitrogen in its several forms in rain and snow during a period of seventeen years:

TABLE 38

NITROGEN ADDITION TO THE SOIL BY RAIN AND SNOW

Nitrogen as	Rain	Snow
	Pounds per Acre	Pounds per Acre
Free ammonia	3.322	0.568
Albuminoid ammonia	0.654	0.194
Nitrites and nitrates	1.762	0.412
Totals	5.738	1.174

[20] Schutt, F. T., and Hedley, M. A., "The Nitrogen Compounds in Rain and Snow," *Transactions of the Royal Society of Canada, 19,* Sect. 3, Series 3, pp. 1-10. 1925.

"The data for the amount of nitrogen furnished yearly per acre show a range of 4.322 to 11.485 pounds. The average for the seventeen-year period is 6.916 pounds." Russell and Richards [21] at Rothamsted, England, found that over a 28-year period an average of 2.64 pounds nitrogen as ammonia (NH_3); 1.33 pounds nitric nitrogen (N_2O_5), and 16 pounds chlorine were added per acre annually by precipitation.

The data on sulfur do not cover such an extended period as on nitrogen, yet are sufficiently conclusive to show that the amount brought down by rain is extremely important in affecting the composition of the soil solution. Stewart [22(1)] found the average annual precipitation of sulfur by rainfall, in Illinois, over a period of seven years, to be 45.1 pounds per acre. At another point, he found an addition of 40.8 pounds per acre (three-year-average). MacIntire *et al.*,[22(2)] in the city of Knoxville, Tenn., found an average annual addition during three years of 124 pounds. Crowther and Steurt [22(3)] at Leeds, England, found an addition of 330, 210, and 160 pounds per acre at various points in the city, and only 65 pounds in the suburbs. Erdman [22(4)] in Iowa found 15 pounds added during a one-year experiment. Crocker [22(5)] calculates (page 135) the amount liberated by the burning of coal and concludes that determinations made on rain-water collected in open country, and showing from 7 to 20 pounds of sulfur per acre per year, are a fair estimation of the amount brought down by precipitation.

Wilson [23] analyzed the rain-water at Ithaca, New York, monthly for nitrogen and sulfur. His results show the following additions to the soil (see Table 39). Samples collected at several

[21] Russell, E. J., and Richards, E. H., "The Amount and Composition of Rain Falling at Rothamsted," *Jour. Agric. Science*, *9*, pp. 309-337. 1919.

[22] (1) Stewart, R., "Sulfur in Relation to Soil Fertility," *Ill. Agric. Expt. Sta. Bul.* *227*. 1920.

(2) MacIntire, W. H., Willis, L. G., and Holding, W. S., "The Divergent Effects of Lime and Magnesia upon the Conservation of Soil Sulfur," *Soil Science*, *4*, pp. 231-235. 1917.

(3) Crowther, C., and Steurt, D. W., "The Distribution of Atmospheric Impurities in the Neighborhood of an Industrial City," *Jour. Agric. Science*, *5*, pp. 391-408. 1913.

(4) Erdman, L. W., 'The Sulfur Content of Rainwater," *Soil Science*, *14*, pp. 363-367. 1922.

(5) Crocker, W., "The Necessity of Sulfur Carriers in Artificial Fertilizers," *Jour. Amer. Soc. Agron.*, *15*, pp. 129-141. 1923.

[23] Wilson, B. D., "Nitrogen and Sulfur in Rainwater in New York," *Jour. Amer. Soc. Agron.*, *18*, pp. 1108-1112. 1926.

TABLE 39

ADDITIONS OF NITROGEN AND SULFUR BY RAIN-WATER AT ITHACA, NEW YORK
(Results Expressed as Pounds per Acre)

Year	Rainfall in Inches	Nitrogen as NH_3	Nitrogen as NO_3	Sulfur
1915–16	30.3	16.3	0.8	...
1916–17	25.4	16.9	1.0	...
1917–18	36.5	16.1	1.6	...
1918–19	30.3	3 3	0.8	27.8
1919–20	24.0	2.5	0.9	24.6
1920–21	25.1	4 7	0.6	26.0
1921–22	31 8	4 0	1.1	33.4
1922–23	31 5	1 6	0.7	35.9
1923–24	24.4	4.0	0 6	45.8
1924–25	29.8	1.5	0.2	47 4
1925–26	35.0	7.6	0.6	65.1

outlying stations, but for a much shorter period, showed variations in amounts in both nitrogen and sulfur.

Not only are nitrogen and sulfur added to the soil by rain and snow, but various salts, especially in the vicinity of large bodies of water, may be added. Clarke (page 57) reports the result of an investigation made in Normandy showing that each hectare of soil received annually in rain the following amounts of salts:

Salt	Kilograms	Salt	Kilograms
$NaCl$	37.5	Na_2SO_4	8.4
KCl	8.2	K_2SO_4	8 0
$MgCl_2$	2 5	$CaSO_4$	6 2
$CaCl_2$	1.8	$MgSO_4$	5 9

The amount of chlorine brought down by rain varies with the distance from the sea, but is shown by Clarke (page 56, cited in **195**) to be considerable. (See Table 40.)

TABLE 40

CHLORINE BROUGHT TO THE SURFACE OF THE EARTH BY RAIN
(Pounds per Acre per Annum)

Locality	Chlorine	Locality	Chlorine
Rothamsted	14 87	Odessa, Russia	17.00
Ceylon	180.63	Barbados	116.98
Calcutta	32.87	British Guiana	129.24
Madras	36.27	New Zealand	61.20

It is impossible to estimate the amount of the other plant food materials added to the soil in the form of dust, salts, gases, etc.

The fact remains that there is an interchange of plant food materials which has a marked influence upon the concentration of the soil solution. That this interchange is in no sense a balanced or equalized one is an important fact, long recognized, and giving rise to the theory of "cyclic salts" or of cycles, discussed in Chapter 25.

244. Total versus Soluble Plant-Food Elements.—The chemical composition of the soil mass is variable **(197)**. The total amount of one or more elements in the soil mass gives no indication of the amount of any one element in a solution obtained from that mass. It is known that the solid portion of the mass is to a certain degree soluble **(208)**, the solubility being due mainly to oxidation, hydration, and carbonation. It is known also that the elements may be in various states of availability to plants. The concentration of the soil solution is known to vary **(234)**, the variability being due to many factors. The factors are interdependent; rarely does the effect of any one predominate throughout the growing season. The action is a continuously changing solubility effect of the different compounds and is influenced by the physical, chemical, and biological properties of the soil mass. But all of the compounds containing the potential plant foods are not influenced in the same manner and to the same degree. It must be remembered: First, that the source of carbon for carbonation is principally the organic matter content of the soil mass. Second, that the gaseous plant-food soil-derived elements, nitrogen and sulfur, are primarily oxidized by biological action, possibly to rather strong acids. Third, that the metallic elements are primarily hydrolized or carbonated. Fourth, that the actions are not independent but are closely related. And, fifth, the fact that one compound is rendered soluble may, when solution is effected, have secondary effects, thus causing other compounds also to go into solution.

245. Biological Influence on Solubility.—The effect of biological activity in the soil mass is, directly or indirectly, to increase solubility. The higher plants may actually cause an etching effect [24] upon smooth surfaces due to an increased solubility. The effect is markedly intensified in the presence of bac-

[24] Fred, E. B., and Haas, A. R. C., "The Etching of Marble by Roots in the Presence and Absence of Bacteria," *Jour. Gen. Physio.*, *1*, pp. 631-638. 1920.

teria. The microbiologic soil population exerts possibly the greatest solubility effects. In this case, the effect is due to certain products that are formed during the metabolic (284) processes (the formation of acids, gases, etc.) or to a stimulative chemical effect. Micro-organisms are extremely active in causing changes in the gaseous elements essential to plants, but are rather passive in causing changes in the metallic. For instance, the compounds containing carbon, nitrogen, and sulfur are rapidly oxidized to carbon dioxide (carbonic acid), nitrous oxide (nitric acid), and sulfur dioxide (sulfuric acid). While carbonic acid is the weakest chemically of the three, it is the most important in the soil mass, due to the consistently large amounts formed. The mineral elements are not directly affected, except for the small amounts assimilated, but those that are split off as waste products tend to form salts. The formation of salts and of various chemically changed soluble products tends to influence the soil solution in such a manner as to increase the solubility of other minerals or materials. Ames [25] found that the oxidative processes of nitrification and sulfofication were quite different in an acidic as compared with a basic soil and that factors favoring one or the other process in the respective soils resulted in a marked difference in the solubility of the elements. (See Table 41.) This point may best be illustrated by a discussion of the factors affecting the solubility of different soil-derived plant-food elements or those elements affecting plant growth from the broadest viewpoint.

246. Influence of Carbon on the Soil Solution.—The element carbon cannot be considered as a soil-derived plant-food element. Its compounds are, however, the main source of soil energy, they are the regulator and initiator of many soil processes and the main support of microbiological functions to be discussed later. In the form of decomposable organic matter carbon practically regulates the process of carbonation. The chemical effects are connected mainly with the production of carbon dioxide,[26] which in turn affects the solubility of the

[25] Ames, J. W., "Solvent Action of Nitrification and Sulfofication," *Ohio Agric. Expt. Sta. Bul. 351.* 1921.

[26] Hibbard, P. L., "Changes in Composition of the Soil and the Water Extract of the Soil, Following Addition of Manure," *Soil Science, 7,* pp. 259-272. 1919.

Parker, F. W., "The Carbon Dioxide Content of the Soil Air as a Factor in the Absorption of Inorganic Elements by Plants," *Soil Science, 20,* pp. 39-44. 1925.

TABLE 41

SOLVENT EFFECT OF NITRIFICATION AND SULFOFICATION AFTER 19 WEEKS' INCUBATION

(Results Expressed as ppm.)

Additions to 500 Grams Dry Soil	Nitrogen as		Citrate Sol. Phosphorus		Water Soluble					
	NO_3	NH_3	At Beginning	At End	Sulfur	Potassium	Calcium	Magnesium	Aluminum	Manganese
Acid Silt Loam Soil:										
None	84	13	45	60	37	18	111	30	0	0
2 gm. $CaCO_3$	128	0	48	54	50	7	270	13	0	0
4 gm. dried blood	294	67	53	63	58	30	255	54	0	34
4 gm. D.B. + 2 gm. $CaCO_3$	462	0	51	54	95	24	736	34	0	0
2 gm. sulfur	6	50	44	99	2143	18	370	103	660	468
2 gm. S. + 4 gm. D.B.	6	246	..	..	1365	52	317	76	234	330
2 gm. S. + 4 gm. D.B. + 4 gm. $CaCO_3$	228	132	..	..	1559	49	1505	113	11	325
Basic Black Clay Soil:										
None	153	3	130	141	87	31	245	41	0	0
4 gm. D.B.	491	25	130	134	90	44	668	97	0	16
4 gm. $(NH_4)_2SO_4$	280	737	125	156	1696	72	1297	183	0	8
2 gm. sulfur	16	67	119	270	2156	48	1173	282	40	48
2 gm. S. + 4 gm. D.B.	12	279	129	244	2225	60	1763	448	52	44
2 gm. S. + 4 gm. $(NH_4)_2SO_4$	42	1071	124	259	3480	85	2080	275	79	56

inorganic materials. As the production of carbon dioxide is a function of the biological soil population, it appears that the action of carbon compounds on the concentration of the soil solution is in part indirect. Jensen [27] studied the solvent action of water-soluble organic matter derived from the decomposition of manures (green and stable), of artificially prepared humus and of osmosed organic solutions; on the calcium, magnesium, iron, and phosphoric acid content of a clay loam and a sandy loam obtained from the Riverside district in California. He found that the solubility of all four of the inorganic constituents was increased from one to five times over the solubility effects of distilled water. The increase was due, partially to the action of the inorganic salts contained in the organic substances or their extracts, and partially to the solvent action of the mineral-free soluble organic compounds.

While the development of soil acidity may cause a decomposition of the mineral carbonates, the application of mineral carbonates, to correct an acid condition, will increase the amount of carbon dioxide produced. On the other hand, if decomposable organic matter is added to a soil, the production of carbon dioxide [28] is stimulated. If it is added with the mineral carbonates, the production of carbon dioxide is increased, but the decomposition of the mineral carbonates is reduced. It appears, however, that while the addition of organic matter increases carbon dioxide production, there may or may not be an increase in the amount of water-soluble plant-food elements. When Hibbard added fresh manure to a soil, the resulting reactions decreased the amount of solubles. When the manure became well decomposed, there was a marked increase in the amount of solubles, hence in the amount of available plant food.

The relation of carbon compounds (particularly organic matter) to the soil-derived plant-food elements is mainly biologic. If the proportion of available energy material to nutrients is too low, a point may be reached when the liberation and accumulation of the soil-derived plant-food elements is retarded. This

[27] Jensen, C. A., "Effect of Decomposing Organic Matter on the Solubility of Certain Inorganic Constituents of the Soil," *Jour. Agric. Resch.*, *9*, pp. 253-268. 1917.

[28] Potter, R. S., and Snyder, R. S., "Carbon Dioxide Production in Soils and Carbon and Nitrogen Changes in Soils Variously Treated," *Iowa Agric. Expt. Sta. Resch. Bul. 39*. 1916.

is due mainly to the limitation of carbon dioxide production. On the other hand, if the proportion should be too high, an injurious effect may be produced, due either to such physical conditions as drying, etc., or to the production of materials that may act as toxins.

247. Nitrogen and the Soil Solution.—In general it may be said that the amount and activity of the nitrogenous constituents of the soil is a microbiological function of the carbon content. The nitrogen compounds of the soil are mainly organic, therefore unavailable to the higher plants. The action of micro-organisms is required to change this unavailable organic nitrogen to an available inorganic form **(295-296)**. The biologic action is apparently governed by the relative amounts of carbon and nitrogen (the carbon-nitrogen ration **(265)**, available for biologic decomposition. It appears that there is a tendency to keep the ratio at approximately 10 to 1, provided of course that other soil factors are favorable for microbiologic development. If the ratio is too wide, the micro-organisms may either waste the excess carbon or may use it as a source of energy for fixing more nitrogen from the atmosphere **(298)**. If the ratio is too narrow, the tendency is to waste the nitrogen **(297)**, or to change such large amounts to the inorganic form that plants are unable to assimilate them. In the latter case, the excess nitrates may either be lost by leaching, etc., or may accumulate to such an extent that they will become toxic.

Organic soil nitrogen is relatively insoluble. In the change, induced by microbiologic action, to the inorganic form, ammonia and nitrates are produced. The former usually occurs in the soil in very small amounts, the latter occurs in much larger amounts. The amount formed is governed by the activity of the soil population. As the activity of the latter is regulated by such factors as moisture, temperature, aeration, reation, food supply, and biological relations, the amount formed is extremely variable. In general, the amount of inorganic nitrogen formed in the soil is much larger during the summer than in the winter.

Nitrate nitrogen is a very elusive and very variable compound in the soil mass. It is highly soluble, readily available to both higher plants and micro-organisms, therefore it becomes easily assimilated, changed, or lost. It is very weakly absorbed by the soil particles, consequently is subject to all water movements.

A rainfall of 1.14 inches on Plat 32 at the Pennsylvania station [29] caused a loss of 80 pounds nitrogen per acre from the 0 to 3-inch depth, of 61 pounds from the 0 to 6-inch depth, and of 68 pounds from the 0 to 24-inch depth. Whiting and Richmond [30] found that during the winter and spring of 1921-22, three similarly treated plots in eight fields in northern and central Illinois lost the following average amounts of nitrogen as the nitrate from the upper 40 inches of soil: check plot 325 pounds per acre, manured plot 227 pounds, and sweet clover plot 206 pounds. During the same season, but in the southern part of the state, four fields, sampled at the same depth, showed a loss of 62 pounds in the check plots, but a gain of 27 pounds for the manured, and of approximately 100 pounds in the case of the plots growing sweet clover. The nitrate nitrogen content of the soil is usually increased by the application of rapidly decomposable organic matter [31] but the results are conflicting when bulky or slowly decomposable organic matter is supplied.[32] Nitrate nitrogen is in greater amounts in non-irrigated than in irrigated soils, is increased in amount by the growing of inoculated legumes,[33] by the use of lime on acid soils,[34] and is conserved by growing crops.[35]

248. Forms of Nitrogen in the Soil.—In spite of the fact that the nitrogenous constituents of the soil have been investigated possibly more thoroughly and extensively than those of any other plant-food element, comparatively little is known of the various forms existing in the soil. This is due almost entirely to a limitation of accurate chemical methods. It is known [36] that

[29] White, J. W., "The Effect of 1.14 Inches of Rainfall upon the Nitric Nitrogen and Acid Content of Plat 32," *Penna. Agric. Expt. Sta. Ann. Rept.*, pp. 67-70. 1913-14.

[30] Whiting, A. L., and Richmond, T. E., "Sweet Clover in Relation to the Accumulation, Loss and Conservation of Nitrates in Soil," *Soil Science, 22*, pp. 1-19, 1926.

[31] Harris, F. S., "Effect of Irrigation Water and Manure on the Nitrate and Total Soluble Salts of the Soil," *Jour. Agric. Resch., 8*, pp. 333-359. 1917.

[32] Thomas, R. P., and Harper, H. J., "The Use of Oats Straw in a System of Soil Fertility," *Soil Science, 21*, pp. 393-400. 1926.

[33] Fred, E. B., and Graul, E. J., "The Gain in Nitrogen from Growth of Legumes on Acid Soils," *Wis. Agric. Expt. Sta. Resch. Bul. 39*. 1916.

[34] Moores, C. A., and MacIntire, W. H., "The Comparative Effect of Various Forms of Lime on the Nitrogen Content of the Soil," *Jour. Amer. Soc. Agron., 13*, pp. 185-205. 1921.

[35] Moores, C. A., "A Comparative Study of the Nitrogen Economy of Certain Tennessee Soils," *Tenn. Agric. Expt. Sta. Bul. 118*. 1917.

[36] Jodidi, S. L., "The Chemical Nature of the Organic Nitrogen in the Soil," *Iowa Agric. Expt. Sta. Resch. Bul. 1 and 3*. 1911.

the inorganic forms consist primarily of ammonium and nitrate compounds, the organic of mono- and di-amino acids, protein compounds, and the so-called "humus" **(225)**. The amount capable of going into solution is usually a very small fraction of the total.[37] (See Table 42.)

TABLE 42

SOLUBLE VERSUS TOTAL NITROGEN IN SOILS[38]

Type of Soil	Total Nitrogen Per Cent	Per Cent of Total Nitrogen			
		Ammonia Nitrogen	Amino-Acids Nitrogen	Nitrate Nitrogen	Soluble Non-Protein N.
Calhoun silt loam.......	0.181	0.60	0.27	0 325	14.45
Miami silt loam	0.161	0.8[illegible]	0 48	0.68	17.10
Miami silt loam	0 130	1[illegible]	0.36	1 43	17.90
Peat soil	3.390	0.2[illegible]	0.26	0.37	4.96

249. Sulfur and the Soil Solution.—The earlier chemical analyses of plants showed only a small amount of sulfur, consequently it was assumed that the soil contained a sufficiency for crop needs. The true sulfur content of plants[39] and the importance of the rôle played by this element have been brought to light primarily during the past decade. It is of interest to note that the earlier investigations[40] made with sulfur were at first concerned mainly with the influence of sulfur or sulfur compounds on the availability of phosphorus. Later studies soon proved that this element played a number of very important rôles in the soil.

[37] Harper compares the total nitrate and ammonia nitrogen content of 24 different soils with indifferent results. See Harper, H. J., "The Ammonia Content of Soil and Its Relation to Total Nitrogen, Nitrates, and Soil Reaction," *Jour. Agric. Resch.*, *31*, pp. 549-553. 1925.

On the other hand, Alway and Bishop show that the humus nitrogen of arid soils is approximately 50 per cent of the total nitrogen content. See Alway, F. J., and Bishop, E. S., "Nitrogen Content of Arid Soils," *Jour. Agric. Resch.*, *5*, pp. 909-916. 1916.

[38] Potter, R. S., and Snyder, R. S., "The Effect of Heat on Some Nitrogenous Constituents of Soil," *Soil Science*, *5*, pp. 197-212. 1918.

[39] Barlow, W. E., "On the Losses of Sulphur in Charring and in Ashing Plant Substances; and the Accurate Determination of Sulphur in Organic Substances," *Jour. Amer. Chem. Soc.*, *26*, pp. 341-367. 1904.

[40] Lipman, J. G., McLean, H. C., and Lint, H. C., "The Oxidation of Sulphur in Soils as a Means of Increasing the Availability of Mineral Phosphates," *Soil Science*, *1*, pp. 533-539. 1916. Also "Sulfur Oxidation in Soils and Its Effect on the Availability of Mineral Phosphates," *Soil Science*, *2*, pp. 499-538. 1916.

It may be said that sulfur acts like nitrogen in the soil, that is, transformation of sulfur compounds or the element itself to available plant-food is a function of microbiological activities. The activities, however, are not so clearly defined, neither is it possible to trace such a complete cycle of events as is the case with nitrogen.

The soil mass contains relatively small amounts of sulfur. The amount (Table 43) closely parallels the amount of phosphorus. The form in the soil mass is not known but it seems probable that the major portion, at least, is in the form of organic matter. This supposition is supported by the fact that the greatest amounts occur in the surface soils. The soil mass usually contains micro-organisms capable of oxidizing both organic and inorganic sulfur. This oxidizing process changes the insoluble element or compounds to the soluble sulfates [41] and may markedly increase the acidity of the mass, especially where large amounts of sulfur are applied. The acidity may be partially overcome by the buffering action **(220)** of the organic and inorganic colloidal material in the soil mass. Its general effect, however, is to increase the solubility of other soil compounds.

Russell [42] classifies the ions present in the soil solution as those which tend to dissolve (N.S., etc.) and those which tend to be precipitated (P.K., etc.). The former are mobile and easily lost, the latter are less mobile, therefore less easily lost from the soil mass. Swanson and Miller[43] show that the losses of organic matter, nitrogen, and sulfur from cultivated soils is quite large. In the case of nitrogen, the amount lost from the soil is partially accounted for by the nitrogen content of the crop. In the case of sulfur, the amount taken up by the crop is insignificant as compared with the total amount lost by the soil. This contention is supported by the work of Ames and Boltz [44] who compare the

[41] Reynolds, E. B., and Leidigh, A. H., "Sulfur as a Fertilizer for Cotton," *Soil Science, 14*, pp. 435-440. 1922.

Shedd, O. M., "The Relation of Sulfur to Soil Fertility," *Kentucky Agric. Expt. Sta. Bul. 188*. 1914.

[42] Russell, E. J., *Soil Conditions and Plant Growth*, pp. 54-56. 1915 ed.

[43] Swanson, C. O., and Miller, R. W., "The Sulfur Content of Some Typical Kansas Soils, and the Loss of Sulfur Due to Cultivation," *Soil Science, 3*, pp. 139-148. 1917.

Swanson, C. O., "The Loss of Nitrogen and Organic Matter in Cultivated Kansas Soils and the Effect of This Loss on the Crop-producing Power of the Soil," *Jour. Ind. Engin. Chem.*, 7, pp. 529-532. 1915.

[44] Ames, J. W., and Boltz, G. E., "Sulfur in Relation to Soils and Crops," *Ohio Agric. Expt. Sta. Bul. 292*. 1916.

TABLE 43

SULFUR AND PHOSPHORUS CONTENT OF VARIOUS SOILS

(Adapted from Crocker)

Region from which Taken	Number Soils Analyzed		Average Per Cent Surface Soils		Average Per Cent Subsoils	
	Surf.	Sub.	S.	P.	S.	P.
Ohio [a]	12	5	.0302	....	.0328	....
Iowa [b]	22	18	.0414	....	.0299	....
Essex, Eng.[c]	21	..	.0204	.1171	....	....
Ohio, Wisconsin, Maryland, Illinois, Alabama, Oklahoma [d]	22	17	.0304	.0754	.0244	.0457
Wisconsin [e]	16	..	.0319	....	....	....
Wisconsin [f]	1	..	.0160	.0616	....	....
Illinois [g]						
Upland soils	58	53	.0373	.0760	.0148	.0457
Swamp soils	39	..	.1220	.0897		
Oregon [h]	10	10	.0273	.0623	.0200	.0714
Kentucky [i]	74	55	.0289	.0960	.0184	.0745
Kansas [j]	11	S.7 P.9	.0356	.0442	.0314	.0404
Michigan, Ohio, Wisconsin, Indiana, Kentucky [k]	34	11	.0250	.1050	.0197	.0429

[a] Ames, J. W., and Richmond, T. E., "Fermentation of Manure Treated with Sulphur and Sulphates: Changes in Nitrogen and Phosphorus Content," *Soil Science, 4*, pp. 78-89. 1917.

[b] Brown, P. E., and Kellog, E. F., "Sulfur and Permanent Soil Fertility in Iowa," *Jour. Amer. Soc. Agron.*, 7, pp. 97-108. 1915.

[c] Dymond, T. S., Hughes, F., and Jupe, C. W. C., "The Influence of Sulphates as Manure upon the Yield and Feeding Value of Crops," *Jour. Agric. Science, 1*, pp. 217-229. 1905.

[d] Eaton, S. V., "Sulphur Content of Soils and Its Relation to Plant Nutrition," *Bot. Gaz., 74*, pp. 32-58. 1922.

[e] Hart, E. B., and Peterson, W. H., "Sulphur Requirement of Farm Crops in Relation to the Soil and Air Supply, *Wis. Agric. Expt. Sta. Resch. Bul. 14*. 1911.

[f] Hart, E. B., and Tottingham, W. E., "Relation of Sulfur Compounds to Plant Nutrition," *Jour. Agric. Resch., 5*, pp. 233-250. 1915.

[g] Mosier, J. G., *et al., Ill. Agric. Expt. Sta. Soil Survey Reports 19, 20,* and *21*, 1921. Peoria, McHenry, and Bureau Counties.

[h] Reimer, F. C., and Tartar, H. V., "Sulphur as a Fertilizer for Alfalfa in Southern Oregon," *Ore. Agric. Expt. Sta. Bul. 163*. 1919.

[i] Shedd, O. M., "The Sulphur Content of Some Typical Kentucky Soils, *Ky. Agric. Expt. Sta. Bul. 174*. 1913

[j] Swanson, C. O., and Miller, R. W., "The Sulphur Content of Some Typical Kansas Soils, and the Loss of Sulphur Due to Cultivation," *Soil Science, 3*, pp. 139-148. 1917.

[k] Woodward, J., "Sulphur as a Factor in Soil Fertility," *Bot. Gaz., 73*, pp. 81-109. 1922.

water-soluble and total sulfur content of several Ohio soils (Table 44), and of McHargue and Peter [45] who estimate that the Ohio River annually drains away approximately 35 pounds of sulfur per acre for the entire river basin.

TABLE 44

WATER-SOLUBLE SULFUR IN OHIO SOILS

(Parts per 2,000,000 of Soil)

SOIL AND TREATMENT	SOLUBLE SULFUR	TOTAL SULFUR
Wooster silt loam—Unfertilized (1896)	58	472
" " " " (1912)	64	412
" " " (Plot 2) acid phosphate	67	440
" " " (Plot 18) manure.	48	464
" " " (Plot 24) acid phosphate ...... Muriate of potash, ammonium sulphate	126	472
Clyde clay—Cultivated	74	1056
Strongsville clay—Uncultivated	26	800

A determination of the total amount of soluble sulfur in the soil apparently does not give an index of the sulfur needs of the plant or of the results that may be expected from sulfur fertilization. Johnston [46] shows that the plant may be able to extract sulfur more readily from humid than from semi-arid soils. Furthermore, humid soils, due to additions from the air, may recuperate more readily in their sulfur content and have a sufficient supply for crop needs.

250. Phosphorus and the Soil Solution.—While much has been written of the action of phosphorus in soils, actually little is known of its relation to the soil solution. Chemists assume that the phosphorus content of a material shall be reported as phosphorus pentoxide P_2O_5. This compound forms three varieties of phosphoric acid: the ortho H_3PO_4, the meta HPO_3, and the pyro $H_2P_2O_7$. The fertilizer industry is interested in the orthophosphoric acid, from which is produced three classes of salts: the primary MH_2PO_4 (the water-soluble phosphates); the secondary M_2HPO_4 (the acid-soluble phosphates), and the tertiary M_3PO_4 (the insoluble phosphates). The primary form is consid-

[45] McHargue, J. S., and Peter, A. M., "The Removal of Mineral Plant Food by Natural Drainage Waters," *Ky. Agric. Expt. Sta. Bul.* 237. 1921.

[46] Johnston, W. W., "The Production and Use of Sulfate in Humid and Arid Soils as Affected by Cropping and Sulfur Treatments," *Soil Science*, *21*, pp. 233-244. 1926.

ered immediately available, the secondary as potentially available, and the tertiary as unavailable or very slowly available. The practice has led to a more or less universal custom of reporting the phosphorus content of the soil as water-soluble, as acid soluble (N/5 HNO_3, 1 per cent citric acid, neutral ammonium citrate, etc.), or as insoluble (usually by difference).

We know little of the phosphorus-bearing compounds as they occur in the soil. Hillebrand [47] states, "The condition of phosphorus when it occurs in only minute amounts is not determined with certainty." Undoubtedly the majority of the soil phosphorus occurs as phosphorite or apatite. These minerals may be regarded as relatively slowly available. Undoubtedly there are also variable amounts of iron and aluminum phosphates, which are relatively insoluble. In addition to the inorganic combinations, a large part of the total phosphorus content of the soil mass occurs in the organic form.[48] Apparently both forms are to a certain degree soluble and present in the soil solution.[49] Pierre and Parker [50] found the average amount of phosphorus in a 1 to 5 extract to be 0.35 ppm. inorganic and 0.22 ppm. organic. The inorganic was found to be available to plants as food, while the organic [51] was apparently unavailable.

The distribution of phosphorus in the soil mass is analogous to the distribution of sulfur. (See Table 43.) The source, however, is not analogous to that of sulfur. Phosphorus is derived practically entirely from the soil mass itself or from soil-forming material. The organic form is derived from the plant remains that first assimilated the element from the soil in which it grew. Usually there is a steady decrease [52] in the amount of total phos-

[47] Hillebrand, W. F., "The Analysis of Silicate and Carbonate Rocks," *United States Geol. Sur. Bul. 700*, p. 250, 1919.

[48] Auten, J. T., "Organic Phosphorus of Soils," *Soil Science, 16*, pp. 281-294. 1923. See also Schreiner, O., "Organic Phosphorus in Soils," *Jour. Amer. Soc. Agron., 15*, pp. 117-124, 1924.

[49] Parker, F. W., and Fudge, J. F., "The Colorimetric Determination of Organic and Inorganic Phosphorus in Soil Extracts and the Soil Solution," *Soil Science, 24*, pp. 109-117. 1927.

[50] Pierre, W. H., and Parker, F. W., "The Concentration of Organic and Inorganic Phosphorus in the Soil Solution and Soil Extracts and the Availability of the Organic Phosphorus to Plants," *Soil Science, 24*, pp. 119-128. 1927.

[51] Parker, F. W., "Plant Growth and the Absorption of Phosphorus from Culture Solutions of Different Phosphate Concentrations," *Soil Science, 24*, pp. 129-146. 1927.

[52] Alway, F. J., and Rost, C. O., "The Vertical Distribution of Phosphorus in the Surface Soils of Prairies," *Soil Science, 2*, pp. 493-497, 1916.

phorus from the surface downward. In some cases, due primarily to rock decomposition or to movement by water, there may be a tendency for an accumulation [53] at certain levels.

In comparison with the other soil-derived plant-food elements, the concentration of phosphorus in the soil solution is rather low, in fact is usually the lowest of all the plant-food elements. The amount, however, is variable. The concentration of phosphorus, calculated as PO_4, in the soil solution ranges [54] from a trace to 12.5 ppm. Soils cropped for long periods without fertilization usually contain the lower amounts. Naturally, soils receiving applications of fertilizers containing phosphorus [55] are usually much higher. It is important to note that all of the soluble phosphorus of the soil mass is not present in the soil solution. It appears that there is, on the part of the soil mass, a remarkable capacity for maintaining the phosphorus concentration in the soil extract. If repeated water extractions are made,[56] the concentration of phosphorus in the extract will remain fairly constant. In fact, in some instances the concentration of phosphorus may, due to a reduction of the salt content in the successive portions, increase. This is due to the fact that the other soluble salts, particularly those containing calcium, have a tendency to reduce the solubility of the phosphates.

It is generally assumed that the losses of soil phosphorus by percolation are insignificant. In the classic investigations at Rothamsted the annual phosphoric acid losses were found to be about 2 pounds per acre. Usually the losses are reported as merely a trace. Apparently the soil mass tends to maintain a certain equilibrium in its total phosphorus content. Robinson and Jones [57] found that additions of phosphatic fertilizers, added to the surface soils, are subject to slow removal and the mass reverts to its original phosphorus status.

The comparatively small amount of phosphorus in the soil

[53] Peter, A. M., "On the Distribution of Phosphorus in a Vertical Section of Bluegrass Soil," *Soil Science*, *2*, pp. 387-393. 1916.

[54] Burd, J. S., and Martin, J. C., "Water Displacement of Soils and the Soil Solution," *Jour. Agric. Sci.*, *13*, pp. 265-295. 1923.

[55] Parker, F. W., and Tidmore, J. W., "The Influence of Lime and Phosphatic Fertilizers on the Phosphorus Content of the Soil Solution and of Soil Extracts," *Soil Science*, *21*, pp. 425-441. 1926.

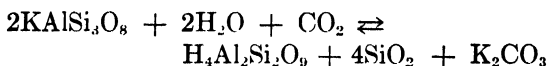
[56] Burd, J. S., and Martin, J. C., "Phosphate Behavior in Soils," *Science*, *58*, p. 227. 1923.

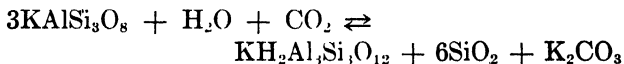
[57] Robinson, G. W., and Jones, J. O., "Losses of Added Phosphate by Leaching from North Welsh Soils," *Jour. Agric. Sci.*, *17*, pp. 94-103. 1927.

solution and the relatively large amount needed by plants [58] indicate the possibility that plants may derive their phosphorus by the action of roots on particles containing this element. This assumption is supported by the experiments of Marias,[59] who shows that root development of plants in sand cultures containing plates of insoluble phosphorus compounds is limited almost entirely to the surface of those plates.

251. Potassium and the Soil Solution.—Potassium is the most abundant in the soil mass of all the soil-derived plant-food elements. It forms 2.6 per cent of the earth's crust **(189)** and, calculated as potash, forms 0.02 to 4.07 per cent of the soil **(197)**. It is derived chiefly from the disintegration of the feldspatic rocks, supposedly as a result primarily of the action of carbonated waters. The decomposition of orthoclase in carbonated water may, according to Van Hise,[60] proceed in two ways:

1. The orthoclase is altered into kaolin with all of the potassium liberated as the carbonate:

$$2KAlSi_3O_8 + 2H_2O + CO_2 \rightleftarrows H_4Al_2Si_2O_9 + 4SiO_2 + K_2CO_3$$

2. The orthoclase is altered into muscovite with the liberation of only two-thirds of the potassium as the carbonate:

$$3KAlSi_3O_8 + H_2O + CO_2 \rightleftarrows KH_2Al_3Si_3O_{12} + 6SiO_2 + K_2CO_3$$

Both of these reactions take place in nature, but their relative importance cannot be stated. It is probable that the alteration to kaolin takes place more rapidly in the humid regions, while the reverse may be the case in regions of simple weathering. In spite of the fact that potassium occurs in relative abundance in all soils, its combinations are in a rather unavailable state. If the other soil-derived elements, particularly nitrogen and phosphorus, were relatively as insoluble, crop production would be a serious problem.

[58] Most physiologically balanced culture solutions contain relatively large amounts of phosphorus. When the amount is reduced in concentration to that of the soil solution, growth is retarded. Hoagland and Martin (*Soil Science, 16*, pp. 367-387. 1923) found that barley would grow in culture solutions containing 1.1 ppm. PO_4. When the concentration was reduced to 0.7 ppm. the growth was considerably reduced.

[59] Marias, J. S., "The Comparative Agricultural Value of Insoluble Mineral Phosphates of Iron, Aluminum, and Calcium," *Soil Science, 13*, pp. 355-409. 1922.

[60] *U. S. Dept. of Agric. Bur. of Soils, Bul. 61*, p. 16. 1914.

The information on the solubility of soil potassium is contradictory. Apparently this element is held in an adsorbed or absorbed state, from which it can be dislodged by replacement. (214). Not only is the potassium ion firmly held by the soil particle, but if soluble potassic compounds be added to the soil, these too may be removed from solution [61] and firmly fixed by the soil. In the laboratory, replacement is usually brought about by the use of such solvents as N/5 HNO_3, normal solutions of ammonium, calcium, or barium chloride, and sometimes other salts, or in the case of electrodyalisis the K ion is replaced by the H ion acting as a base. In the soil, replacement is brought about by the various materials used as fertilizers, by the presence of soluble salts, and by the action, direct and indirect, of carbon dioxide.

Fraps [62] differentiates between the insoluble and potentially available potassium on the basis of solubility in N/5 HNO_3. The amount soluble in the acid is called "active potash." It appears that soils containing 50 ppm., or less active potash, are deficient in the element potassium, while soils containing 200 ppm. or more may have a sufficient amount of potassium for crop needs. If the active potash is in excess of plant needs, the plant will take up an excess. The percentage in the plant will decrease as the active potash in the soil decreases. "The quantity of active potash [63] lost is 60 to 90 per cent of that taken up by the crop, until the active potash is reduced so that the potash removed actually comes from the insoluble potash compounds and not from the active potash."

The main sources of soil potassium are the minerals biotite, muscovite, orthoclase, and microcline (193). The solubility of these minerals in the various solvents common to the soil is shown in Table 45.

When these minerals are applied to the soil as a potassic fertilizer and crops grown, it appears that the plants are able to extract different amounts of potassium from the different minerals.

[61] Morse, F. W., and Curry, B. E., "The Availability of the Soil Potash in Clay and Clay Loam Soils," *New Hampshire Agric. Expt. Sta. Bul. 142.* 1909.

[62] Fraps, G. S., "The Active Potash of the Soil and Its Relation to Pot Experiments," *Texas Agric. Expt. Sta. Bul. 145.* 1912.

[63] Fraps, G. S., "The Effect of Additions on the Availability of Soil Potash, and the Preparation of Sugar Humus," *Texas Agric. Expt. Sta. Bul. 190.* 1916.

TABLE 45

AVERAGE SOLUBILITY OF POTASSIUM IN COMMON SOIL-FORMING MINERALS[64]

(Results Expressed as ppm. K_2O)

MINERAL	DISTILLED WATER	CARBONATED WATER	CARBONATED WATER PLUS $Ca(HCO_3)_2$
Biotite	26.3	261.3	257.5
Muscovite	24.2	169.4	170.5
Orthoclase	20.4	94.0	96.7
Microcline	18.1	61.4	60.9

252. Calcium and Magnesium and the Soil Solution.—The two elements, calcium and magnesium, play such similar rôles in the soil that they are usually studied together. Compounds of these two elements are frequently referred to as lime. As soil acidity may be corrected by the use of lime, and as the removal of lime compounds from the soil mass is one of the factors contributing to soil acidity, it is usually assumed that an acid soil is deficient or lacking in the elements calcium and magnesium. Such is not the case. An acid reaction merely means that these elements are not present in the carbonate form. The solution of an acid soil may contain large amounts of both elements. MacIntire and MacIntire and Shaw[65] found that a brown loam soil, acid in reaction, lost by leaching in four years 898 pounds of calcium and 336 pounds of magnesium calculated as the carbonate. The original soil contained 8990 pounds of calcium and 20,440 pounds of magnesium calculated as the carbonate. As the soil was devoid of carbonates, this loss was considered as having been derived from the hydrolysis of the native silicates and by the neutralization of biological end-products.

When lime was added at the rate of 200 pounds CaO-equivalent, either as the hydroxide, ground calcitic, or dolomitic limestone, and at different degrees of fineness, the amount lost by leaching increased. The additions were made to the surface and to the subsoil. The leachings were analyzed for a period of four

[64] Plummer, J. K., "Availability of Potash in Some Common Soil Forming Minerals and Effect of Lime on Potash Absorption by Different Crops," *Jour. Agric. Resch.*, *14*, pp. 297-315. 1918.

[65] MacIntire, W. H., and Shaw, W. M., "The Disintegration of Limestone and Dolomite Separates as Influenced by Zone of Incorporations," *Soil Science*, *20*, pp. 403-417. 1925.

MacIntire, W. H., "Influence of Form, Soil-Zone, and Fineness of Lime and Magnesia Incorporations upon Outgo of Calcium and Magnesium," *Soil Science*, *21*, pp. 379-391. 1926.

years. There was a marked increase in the amount of calcium in the leachings, especially where the hydrate or the calcitic material was used. The loss was less when the additions were made to the surface than when made to the subsurface. The hydrate lost 6.8 per cent of the total addition made to the surface, and 59.2 per cent of the additions made to the sub-surface, during the four-year period. The ground calcitic material lost from 1.8 to 5.8 per cent from the surface and 14.0 to 33.0 per cent from the sub-surface during the same time. The dolomitic material lost from 2.2 to 7.8 per cent from the surface and 7.2 to 20.7 per cent from the sub-surface. The amount of magnesium lost was not so great as the amount of calcium. The addition of the hydrate to the surface caused an increased loss of magnesium equivalent to 7 pounds per year, but when added to the subsurface there was a repressed effect resulting in a decrease of 35 pounds from that of the control. Similar results were secured in the case of the calcitic material and of dolomite added to the surface. When dolomite was added to the sub-surface, however, there was a marked increase of soluble magnesium resulting in from 8.7 to 34.4 per cent of the amount added being leached out in four years.

Not only does the addition of lime compounds to a soil increase the calcium-magnesium outgo, but it also increases the sulfur-nitrogen losses. MacIntire[66] found, in the experiments described above, a slight increase in sulfur losses due to the additions of lime, and this in spite of the fact that a large amount of sulfur was added by rain (approximately 180 pounds per acre). The amount of nitrate nitrogen lost from the same soil (original total nitrogen content, 0.105 per cent) and during the same period, was (calculated as pounds nitrogen per two million pound acre) surface 169 pounds and sub-surface 169 pounds. The addition of lime, as above, stimulated the loss of nitrate nitrogen from both zones. Hydrated lime increased the loss 26 pounds in the surface but only 5 pounds in the sub-surface. Both calcitic and dolomitic limestones increased the loss in both zones, the finer material causing the greater losses, which ranged from a few to 75 pounds increased loss.

[66] MacIntire, W. H., "Influence of Form, Soil-Zone, and Fineness of Lime and Magnesia Incorporations upon Outgo of Sulfates and Nitrates," *Soil Science*, *22*, pp. 21-30. 1926.

253. Aluminum and the Soil Solution.—In spite of the fact that aluminum occurs in great abundance in nature, it is relatively insoluble when the soil mass is neutral in reaction. This fact is shown by the small amounts found in natural waters. When the soil mass becomes either acid or alkaline, the solubility of the aluminum compounds is markedly increased. The aluminum compound most readily attacked is said to be gibbsite AlO_3H_3.[67] It is believed, however, that aluminum oxide is present in certain clays.[68]

The relation of the solubility of aluminum to an acid or an alkaline solution is shown in Table 46:

TABLE 46

SOLUBILITY OF ALUMINUM IN WATER AT THE INDICATED pH VALUES (Al_2O_3 in Solution Expressed as ppm.)

pH	Al_2O_3	pH	Al_2O_3	pH	Al_2O_3
3.92	1000.0	4.51	6.5	8.95	34.6
3.94	600.0	4.66	2.3	9.28	63.4
3.95	400 0	5.22	1.2	9.49	124.0
3.96	200 0	5 40	0.8	9.75	200.0
4.02	130 0	7.00	0.4	10.10	400.0
4.19	79.0	7.55	2.0	10.15	600.0
4.27	43.0	8.35	8.4	10.43	1100.0

Between the range pH 4.27 to 8.95 only small amounts of aluminum are in the soil solution. An increase of the acidity or alkalinity increases the solubility. The increase is very rapid and may reach the point where the presence of soluble aluminum may prove a toxic or deterrent factor in plant growth. As soluble aluminum compounds tend to react with soluble phosphorus compounds, forming insoluble aluminum phosphates, the presence of the former tends to depress the availability of the latter. Apparently the presence of a toxic soil condition, due to the presence of soluble aluminum, may be corrected by an application of either lime, soluble phosphorus, or both.[70]

[67] Mirasol, J. J., "Aluminum as a Factor in Soil Acidity," *Soil Science*, *10*, pp. 153-218. 1920. See also Denison, I. A., "The Nature of Certain Aluminum Salts in the Soil and Their Influence on Ammonification and Nitrification," *Soil Science*, *13*, pp. 81-106. 1922.

[68] Edwards, M. G., "The Occurrence of Aluminum Hydrate in Clays," *Econ. Geology*, *9*, pp. 112-121. 1914.

[69] Magistad, O. C., "The Aluminum Content of the Soil Solution and Its Relation to Soil Reaction and Plant Growth," *Soil Science*, *20*, pp. 181-213. 1925.

[70] Burgess, P. S., and Pembe, F. R., "Active Aluminum as a Factor Detrimental to Crop Production in Many Acid Soils," *R. I. Agric. Expt. Sta. Bul. 194*. 1923.

CHAPTER 20

THE CHEMICAL AND PHYSICAL PROPERTIES OF SOILS IN RELATION TO PLANT GROWTH

The higher forms of plant life live partially in and partially above the soil. Their growth is dependent upon the condition of the soil in which they are growing, the climatic conditions above the soil and the plant itself. These three main factors are influenced by many minor conditions, each of which may become of prime importance. For instance, the plant itself is dependent upon: (1), its vital elements or the ability to utilize nutrients, (2), its climatic adaptation, the ability to survive under local climatic changes, (3), its leaf area, the ability to serve as an efficient manufacturer of plant food under the conditions of growth, (4) its root development, its foraging and feeding powers, (5), drought resistance, (6), disease resistance and (7), its inherited characteristics that enable it to survive. The growth of the plant above the soil is dependent upon the climatic effects; for instance, the length of the growing season, precipitation, humidity, wind velocity, temperature, light and altitude.

254. The Soil as Related to Plants.—It is possible to select certain kinds of plants and place them in certain climatic areas hoping to secure certain results. The resultant growth and crop production may not be all that are desired. The reason is usually, in spite of normal climatic and plant characteristics, that crop production is limited because of the conditions and properties of the soil. The soil conditions may be listed as follows:

1. *The physical properties:* The structure, consistence, texture of the soil mass, its water-air-solid relationships, its temperature changes and its profile characteristics.

2. *The chemical properties:* The ability of the soil mass to function as a source of supply of soil-derived plant-food materials. The supply must be, to a certain degree, balanced and in sufficient amounts. Further, the chemical processes must be such as to produce compounds acceptable for healthy plant growth.

Also the chemical changes cannot be such as to render the compounds subject to excessive losses.

3. *The biological properties:* The presence of a soil population capable of initiating such chemical changes as would be favorable to plant growth. Such a population would be capable of decomposing plant remains in such a manner that plants could utilize the end-products with the greatest degree of efficiency and cause such changes as would render the unavailable soil-derived plant-food elements more available.

The physical properties and the biological properties of the soil mass are closely connected with the chemical functions. The physical and the biological properties may be regarded as those factors governing the chemical activities taking place in the great natural stage of nature, the soil mass. A proper combination of the physical properties prepares the stage for the proper functioning of the chemical reactions. The latter are activated, initiated, stimulated, retarded, or changed by the biological functions.

255. Plants and the Soil Profile.—The plant does not occupy exclusively that portion of the soil subject to tillage. Its roots penetrate to various depths **(180)**, consequently its activities in the soil are governed by the condition of the several horizons, or more correctly the condition of the soil profile. The profile **(55)**, however, is not homogeneous throughout its depth. The zone of eluviation (Horizon A) is quite different physically and chemically from the zone of illuviation (Horizon B).

256. Rawness of Subsoils.—It is generally conceded that, under favorable conditions, plants will develop in surface soils. If, however, the surface soil is removed, plants may or may not develop in subsoils. The usual assumption is that under humid conditions the subsoils are "raw," unproductive, but under arid or semi-arid conditions may be productive. The evidence on this point is conflicting. Alway [1] *et al.* found some of the subsoils of eastern Nebraska to be very unproductive insofar as non-legumes were concerned, but capable of supporting a luxuriant growth of inoculated legumes. Lipman [2] found that certain subsoils of

[1] Alway, F. J., McDole, G. R., and Rost, C. C., "The Loess Soils of the Nebraska Portion of the Transition Region. VI. The Relative 'Rawness' of the Subsoils," *Soil Science*, *3*, pp. 9-35. 1917.

[2] Lipman, C. B., "On the 'Rawness' of Subsoils," *Science* (n. s.), *46*, pp. 288-290. 1917.

the arid section were also unproductive in the case of non-legumes. Harmer[3] tested the productivity of seven Minnesota subsoils for inoculated alfalfa and found that five of them were unproductive, while two were as productive as the surface soils. McMiller[4] studied the causes of the unproductivity and found that applications of soluble potash and phosphoric acid fertilizers rendered the unproductive subsoils as productive as the corresponding surface soils. Weaver[5] shows that root development of plants is an environmental factor and that the greatest concentration of roots is in the area of the greatest concentration of available plant nutrients. The general form of the root is governed by heredity, but its activity and growth are very responsive to its environmental conditions. Wet, poorly aerated soils, especially in the early life of the plant, promote a shallow root system. A moderately dry soil will produce a deeper and more branched root. The presence of "nitrates inhibits root penetration and promotes increased branching. Phosphates are successfully used in promoting deep rooting. Deep intertillage frequently results in root injury and decreased yields. Mulching and lack of tillage often promote shallow root development. Soil temperature not only has a distinct effect upon root growth but affects it indirectly through soil aeration." In fact, "the interrelation of edaphic factors to root activities is complex."

257. The Plant as Related to Soils.—The relation of the plant to the soil has been the subject of extensive investigation. The soil, however, is such a complex material that, in order to control all factors, the major part of the studies have been conducted under various conditions approximating those of the soil.

258. Physiological Requirements of Plants.—A long series of plant nutrition studies in water culture[6] has developed the

[3] Harmer, P. M., "The Relative 'Rawness' of Some Humid Subsoils," *Soil Science*, *5*, pp. 393-401. 1918.

[4] McMiller, P. R., "Some Notes on the Cause of the Unproductivity of 'Raw' Subsoils in Humid Regions," *Soil Science*, *7*, pp. 233-236. 1919.

[5] Weaver, J., *Root Development of Field Crops*, pp. 53-91. McGraw-Hill Book Co.

[6] A review of the subject of salt requirement and salt ratios, also a plan for the determination of an optimum solution, is given by Tottingham, W. E., "A Quantitative Chemical and Physiological Study of Nutrient Solutions for Plant Culture," *Physiol. Res.*, *1*, pp. 133-145. 1914. See also Livingston, B. E., "A Plan for Coöperative Research on the Salt Requirements of Representative Agricultural Plants," *Division of Biology and Agriculture of National Research Council.* Edited by B. E. Livingston, Laboratory of Plant Physiology, Johns Hopkins University, Baltimore, Md. 1919.

following principles: First, a certain definite number of chemical elements is absolutely essential for plant growth. The number may vary in certain cases. Second, the elements are derived from chemical combinations either from the soil particle, or as is usually the case, from certain salts. Third, certain combinations or ratios of salts are more beneficial than others and these ratios may be varied to a certain extent without appreciable change in yield. Fourth, The efficiency of water cultures depends upon three variable factors or conditions, namely, total concentration,[7] chemical elements used, and the relative proportion of each. Fifth, the rate of assimilation by the plant varies with its development. An element may be assimilated in large, medium, or small amounts during the earlier stage of growth and in entirely different amounts during succeeding stages. Sixth, the lack of an element produces a more or less pronounced pathological condition. And seventh, one element may to a limited extent replace another element.

259. The Plant as a Physiological Factor.—Plants obtain all their ash constituents from the soil. In other words, the majority of plants obtain all elements except carbon, hydrogen, and oxygen from the soil. The hydrogen and the oxygen may be assumed to be taken from the soil as water. Apparently plants (excepting some microscopic forms) are unable to utilize the carbon from carbonaceous compounds, but are dependent upon the very small amount in the atmosphere. In general, the dry weight of plants consists of 95 per cent carbohydrates, in the approximate proportion of CH_2O, and only 5 per cent ash constituents. The carbon dioxide of the air is fixed as carbohydrate in the plant mainly as a result of photosynthesis, by higher plants. In the storage of carbon, a very important process takes place. *For each gram of carbon dioxide decomposed in photosynthesis, from 2.2 to 3.6 gram calories of energy are stored in the resulting carbohydrate.* This energy, when added to the soil in the form of plant remains, may be considered from the physiological standpoint as *the life-giving principle of the soil mass.*

260. The Feeding Power of Plants.—It has long been recognized that different species of plants vary greatly in their ability

[7] The plant physiologist may express concentration as osmotic pressure in atmospheres. The osmotic pressure of the solution in soils varies widely, from 0.024 atmosphere in peat to 12.04 atmospheres in clay. (*Mich. Tech Bul. 24*, p. 17.)

to secure their soil-derived nutrients. Some plants are able to survive under conditions that would be fatal to others. Some plants are known as strong feeders, growing under a wide range of conditions, others require the necessary conditions for their growth. This ability to secure the necessary mineral nutrients from the soil is spoken of as "the feeding power of plants."

At the present time, the information on the feeding power of plants is rather confusing. Undoubtedly the differences cannot be limited to any one factor, for instance, soil acidity, acidity of the plant juice, production of carbon dioxide by roots, etc. Truog[8] shows that the differences in the feeding power of common agricultural plants are due to several factors, "some of which are concerned with external equilibrium around the feeding roots, and others with internal equilibrium conditions inside the plant where the elements are actually used." "In case two soluble products are formed in the feeding region of the roots, due to the action of carbonic acid on a mineral as in the case with rock phosphate, the feeding power follows the law of mass action and chemical equilibrium, being dependent on the removal of both of the soluble products either by the plant or partly by the plant and partly in other ways; thus plants with a high content of calcium feed strongly on rock phosphate because they remove both the soluble phosphate and soluble calcium bicarbonate in proper proportion. If only one soluble product is formed as is the case with feldspar, the feeding power of the plant for the potassium depends on its ability to utilize potassium from a dilute solution which in turn depends largely on the acidity of the plant sap; the less acid sap the greater the ability of the plant to utilize potassium from this source due to the fact that potassium is more easily and completely precipitated in the form of plant compounds in the less acid sap."

"The feeding power of a plant for calcium which is used for the regulation of the reaction of the plant sap and colloidal system, and precipitation of acids, or for other elements used for these purposes, is also dependent upon the reaction of the plant sap but the relation is opposite to that of potassium; the more acid the plant sap the more easily can the plant compete with another acid system—the soil solution of an acid soil, for needed

[8] Truog, E., "The Feeding Power of Plants," *Science* (n. s.), *56*, pp. 294-298. 1922.

basic materials." The relation of the feeding power of plants to base-forming elements used for purposes other than the regulation of the reaction and precipitation of acids is perhaps the same as for potassium. There are undoubtedly many other factors that affect the feeding powers.

Cooper and Wilson [9] indicate a striking correlation between the electromotive series and the absorption of plant nutrients. They state, "The electromotive series may be the key to many of the perplexing problems of plant and animal physiology. The various ions differ very much in the voltage they produce. Such ions as K, Na, and Ca produce high voltages, other ions, such as Mg, Al, Mn, NH_4, amines and other basic nitrogenous materials, produce medium voltages, while still other ions, such as Fe, H, As, Cu, Hg, etc., produce very low voltages. Various plants and animals apparently tolerate different potential levels. Many crop plants, such as alfalfa, sweet clover, celery, barley, millet, asparagus, beets, etc., seem to be tolerant of very high electrical potentials, as, for example, the potentials produced by high concentration of such ions as K, Na, and Ca, often encountered in semi-arid to arid climates. Other plants, such as blackberry, blueberry, cranberry, raspberry, strawberry, oats, buckwheat, red top, cotton, sweet potatoes, watermelon, etc., grow well at relatively low potential levels as for example, the potentials produced by high concentration of such ions as Mg, Al, Mn, NH_4, amines, protein acid salt ions, Fe, H, etc."

261. Soil-Plant Competition.—The soil particle has a certain tendency to regain materials lost to the soil solution, either by exchange or by adsorption. When the particles of the soil mass are well supplied with plant food ions, the plant has little difficulty, under favorable conditions, of extracting them. When, however, the soil mass becomes deficient in these elements, the adsorptive power of the soil particle may equal that of the plant, with the result that growth is retarded. This condition may be overcome in most cases by the use of fertilizers. If, however, the condition of the soil mass is such that it contains an excess of H ions, acting as metallic ions (**214**), there may be a withdrawal of the fertilizer ions from the soil solution and

[9] Cooper, H. P., and Wilson, J. K., "Correlation between Electromotive Series and Oxidation Potentials and Plant and Animal Nutrition," *Science* (n. s.), *66*, pp. 629-631. 1927.

TABLE 47

THE RELATION OF NORMALITY, pH, ACTIVE ACIDITY, SOIL ACIDITY, AND PLANT GROWTH[10]

NORMALITY HCl	pH	ACTIVE ACIDITY *	DESCRIPTIVE TERMS	AREAS OF PLANT PREFERENCE
.0001	3.1 ↓ 4.0	8,000 ↓ 1,000	Very High Strong Superacid Acidity Low	Acid limit
.00001	4.1 ↓ 5.0	800 ↓ 100	Strong High Mediacid Acidity Low	White cedar, Scrub oak, Arbutus, Cranberry, Bluebeard, etc.
.000001	5.1 ↓ 6.0	80 ↓ 10	Medium High Subacid Acidity Low	Fir, Spruce, Pine, Peanut, Potato, Dewberry, Raspberry, etc.
	6.1 6.9	8 ↓ 0.5	Slight High Minimacid Acidity Low	Redtop, Lupine, Oats, Turnip, Flax, Sorrel, Cowpea, Lima bean, Corn, most vegetables and fruits Alfalfa and most legumes The circumneutral area in which practically all economic crops make their best growth
	7.0	0.0	Neutral	
NaOH		Active Alkalinity		
	7.1 7.9	0.5 8	Slight Low Minimalkaline Alkalinity High	
.000001	8.0 8.9	10 ↑ 80	Medium Low Subalkaline Alkalinity High	Area tolerated but not preferred by economic plants
.00001	9.0	100	Medialkaline	Alkaline limit

* Active acidity is the amount of ionizable hydrogen present in a liter of pure water.

an adsorption or absorption on the surface of the particle from which the plant may or may not be able to extract them. The action may be physical, chemical, or physico-chemical.

262. Soil Reaction and Plant Growth.—Most soils are well buffered, therefore have a strong tendency to maintain a certain constancy of reaction. The ideal reaction from the standpoint of most agricultural plants is from slightly acidic to neutral. The activities of nature, coupled with the practices of man, tend to change the reaction. Thus by leaching, removal of crops, wasteful cultural practices, etc., soils tend to become more acid in the humid areas, or by the use of irrigation waters containing

[10] Adapted from Wherry, E. T., "Soil Reaction in Relation to Horticulture," *American Horticultural Society Bul. 4.* 1926. Washington, D. C.

soluble salts become more alkaline in the semi-arid or arid regions. In nature, certain groups of plants have adapted themselves to various soil conditions, consequently may be found growing in either extremely acid or very alkaline soils. In general, it may be said that most agricultural plants are unable to survive under extremes greater than pH 4.0 or pH 8.5 to 9.0. The range for most plants is, however, approximately between the range pH 5.5 to pH 7.5.

The relation of soil reaction to plant growth is shown by Table 47.

263. Soil Plant Interrelations as Affecting Plant Growth.—The complex soil and plant factors [11] affecting plant production are closely interrelated. A certain soil condition may be changed by growing plants, for instance color, structure, etc. On the other hand, a certain plant condition, for instance a specific crop, may modify the relationship of the soil to the succeeding crop and provide increased or decreased yields.

264. Relation of Plant Remains to the Plant-Food Content of the Soil.—When plant remains are added to the soil mass, they decompose. The mineral elements of the plant are changed to a condition whereby they may become available as food for the succeeding crops. Salter [12] states (page 403), "Averages of analyses of mineral soils show that of the total amount in soils, approximately 95 per cent of the nitrogen, 33 per cent of the phosphorus, and appreciable amounts of the potassium, sulfur and calcium are contained in the organic matter. In the usual fertile soil, these amounts may be of sufficient magnitude to be of considerable consequence. In addition, a definite portion of the organic nutrients will be utilized by micro-organisms in the

[11] The relation of soils and crops is brought out by the work reported by:

Lyon, T. L., "The Effect of Some Legumes on the Yields of Succeeding Crops," *New York Agric. Expt. Sta., Cornell Univ. Bul.*, p. 447. 1925.

Hartwell, B. L., and Damon, S. C., "The Influence of Crop Plants on Those Which Follow. I.," *R. I. Agric. Expt. Sta. Bul. 175*. 1918.

Hartwell, B. L., Pember, F. R., and Merkle, G. E., "The Influence of Crop Plants on Those Which Follow. II.," *R. I. Agric. Expt. Sta. Bul. 176*. 1919.

Hartwell, B. L., Smith, J. B., and Damon, S. C., "The Influence of Crop Plants on Those Which Follow. III," *R. I. Agric. Expt. Sta. Bul. 2'0*. 1927.

Burgess, P. S., "The Yield and Mineral Content of Crop Plants as Influenced by Those Preceding," *R. I. Agric. Expt. Sta. Bul. 198*. 1924.

[12] Salter, F. J., "The Chemical Composition of Soil Organic Matter as Related to Its Effectiveness," *Jour. Amer. Soc. Agron., 19*, pp. 397-411. 1927.

soil in the process of decomposition and this amount will only become available as their bodies undergo decay."

In the process of decomposition, more and more of the insoluble plant compounds become soluble. It frequently happens that losses by percolation, run-off, etc., may occur, if the succeeding crop is not present or if the action is too rapid. All of the gaseous elements may be lost directly to the air; thus, if the losses of nitrogen and sulfur, in particular, are too great, a serious limitation of crops may result.

265. The Nitrogen-Carbon Ratio.—It is believed that the ratio existing between the amounts of nitrogen and carbon (as organic carbon) in the soil mass is an indication of its crop-producing powers. Brown and Allison [13] state on page 49, "Experience has shown that, if the ratio narrows beyond a point of about 1 to 10, crop yields may be reduced, evidently because of an insufficient production of available nitrogen, phosphorus, and potassium. On the other hand, if the ratio was 1 to 12 or above, bacterial activities apparently occur to a satisfactory extent and sufficient amounts of soluble plant-food are produced for good crop growth. This is actually the case in humid soils." This assumption is supported by Russell,[14] who states, "No matter what substance is added to the soil—whether cellulose, starch, sugar, protein, farmyard manure—it rapidly undergoes decomposition in such a way that the final ratio C/N is much the same as it was originally." In a surprisingly large number of cases in humid conditions, the ratio stands at about 10; thus it is the same on the Broadbalk plot unmanured since 1839 as on the adjoining plot receiving 12 tons of farmyard manure annually since 1843; it is approximately the same as at Woburn on a sandy soil, and as in Texas and Iowa." [15] On the other hand, Read [16] shows that there is no correlation between crop yields of corn and wheat, on 37 soil types, found in Iowa, Missouri, Kansas, Minnesota, Wisconsin, West Virginia, North Dakota, and

[13] Brown, P. E., and Allison, F. E., "The Influence of Some Common Humus-forming Materials of Narrow and of Wide Nitrogen-Carbon Ratio on Bacterial Activities," *Soil Science*, *1*, pp. 49-75. 1916.

[14] Russell, E. J., *Plant Nutrition and Crop Production*, p. 66. University of California Press. Berkeley, Cal., 1926.

[15] The work of Allison, *Soil Science*, *24*, pp. 79-90 (1927) supports this contention.

[16] Read, J. W., "Practical Significance of the Organic Carbon-Nitrogen Ratio in Soils," *Soil Science*, *12*, pp. 491-495. 1921.

California. The value for the organic carbon-nitrogen ratios in these soils ranged from 10.74 in Fargo (N. D.) to 4.51 in Waukesha (Wis.) silt loam. The lowest yield of corn, 23 bu. per acre, was obtained on Oswego (Kan.) silt loam with a ratio of 10.57, while the Waukesha (Wis.) silt loam, with the lowest ratio, 4.51, produced a yield of 46 bu. per acre. None of the yields were influenced by the use of fertilizers.

266. The Soil Solution and Plant Growth.—The composition of the soil solution, its constancy, and its rate of renewal vitally affect the crop-producing power of the soil itself. While its composition may be explained on a chemical basis, it is not a result of a direct chemical action. It is markedly influenced by biological activities which induce chemical changes. As a consequence the nutrients required by plants are brought into solution largely as biologically formed materials. These materials tend to react in all ways that affect solubility. Consequently if the soil mass is deficient in any particular ion, for instance, calcium,[17] the resulting soil solution and the soil mass itself must be regarded as being essentially deficient in that element from the standpoint of plant growth. As various bases are constantly being lost from the soil, in excess of the acids, the tendency under humid conditions is to aggravate any acidic condition.

As a soil becomes more acid, its crop-producing powers become weaker. This lowering of productivity is not necessarily due directly to the pH, but to its indirect [18] effects. For instance, as the acidity is increased, pH 5.0 or greater, compounds of aluminum, manganese, etc., becomes soluble and many reach a point where their concentration in the solution is toxic to plant growth. As soluble aluminum compounds tend to react with phosphates and form insoluble compounds, an insufficient supply of phosphorus may become involved. The situation is further aggravated by the inadequacy of the calcium supply.

267. Availability of the Soil-Derived Plant-Food Elements.—It is a well-known fact that plants can only assimilate their soil-derived plant-food in a soluble state, *i.e.* from the soil solution. The total amount of plant food elements in the soil mass

[17] Burd, J. S., "Relation of Biological Processes to Cation Concentration in Soils," *Soil Science, 20*, pp. 269-283. 1925.

[18] Robinson, G. W., and Williams, R., "Base Exchange in Relation to the Problem of Soil Acidity." *Trans. Faraday Soc., 20*, pp. 586-593. 1925.

(196) is no indication of the amount in the soil solution. Further, there is no laboratory method or combination of methods whereby the plant response on a specific soil can be accurately forecast. The plant itself is, however, an accurate indicator of the condition or availability of the plant food elements in the soil mass. It shows by its growth whether or not the soil-derived plant-food elements [19] are capable of being assimilated. In other words, the plant indicates the relative availability of the elements. As there are many gradations, the terms *available, potentially available,* and *unavailable* are applied to the *soil-derived plant-food elements.*

268. Excesses and Deficiencies.—In spite of the fact that laboratory methods fail to accurately interpret **(98, 202)** the crop-producing power of the soil, the plant itself proves to be a very efficient indicator. It may indicate by various characteristics during its development, certain soil conditions and certain soil-derived nutritional relationships, for instance, an excess or deficiency of one or more of the plant food elements. Some plants are more efficient as indicators of certain conditions than are others. On the other hand, a certain soil condition may cause varying crop response in different plants. The following is a brief discussion of the effects of excesses and deficiencies of the more important soil-derived plant-food elements on plant growth.

I. Calcium.—A deficiency of calcium usually indicates an acid condition of the soil. An excess usually indicates calcareous condition. The latter may be the basis of a saline, alkaline, or an alkali soil. The various soil horizons may be neutral, acidic, or calcareous.

Plants preferring a mediacid or a subacid reaction (see Table 47) usually are not tolerant or are injured by a calcareous condition, the injury taking the form of a stunted growth or, in the case of an excess, a uniform chlorotic appearance. Plants preferring a minimacid or neutral reaction [20] usually are not injured by a calcareous condition unless the amount is excessive; for instance, above pH 8.5.

II. Nitrogen.—Plants are more reliable indicators of nitrogen excesses and deficiencies than of any other soil-derived plant-

[19] The distinction between plant food and plant food element is marked. The student is urged to consult the Glossary.

[20] Breazeale, J. F., "Alkali Tolerance of Plants Considered as a Phenomenon of Adaptation," *Ariz. Agric. Expt. Sta. Tech. Bul. 11.* 1926.

food element. As the biological oxidation and fixation of nitrogen (298) is controlled in part by the reaction of the soil mass, the calcium balance markedly affects the nitrogen supply. The latter is continually fluctuating. Usually the amount in the soil mass is not sufficient for crop production. A marked deficiency is evidenced by a yellowish color and poor growth. A normal amount is indicated by a healthy green coloration of the leaves. Under some conditions, the amount of nitrogen may be excessive, in which case the plant may be markedly stimulated in vegetative growth, producing small and immature fruit. In case of great excesses, the plant quickly dies.

III. Phosphorus.—Phosphorus is usually a limiting element in the soil mass. Its compounds in nature are so insoluble that excesses (which are rare) have little effect upon plant growth. Its availability [21] apparently is not markedly affected by the reaction of the mass. A deficiency is usually indicated by a stunted root growth, lack of nodulation in the case of the legumes, and the production of immature or shrunken seeds.

IV. Potassium.—This element is usually in abundance in all soils, yet many of the plants growing on these soils will show a stimulated effect when soluble potassic fertilizers are applied. Its lack of availability is indicated in a wrinkled leaf, the appearance of yellow spots in the leaf, and possibly followed by a dying at the tip and from the edges inward. The plant usually shows a generally stunted, blotchy appearance in cases of excessive deficiencies.

There are many other indicators [22] of soil excesses or deficien-

[21] Ames, J. W., and Schallenberger, C. J., "The Availability of Phosphorus in Calcareous and Non-Calcareous Soils," *Ohio Agric. Expt. Sta.* (Wooster) *Bul. 380.* 1924.

[22] For general reference, see:

Burgess, P. A., and Pember, F. R., "Active Aluminium as a Factor Detrimental to Crop Production in Many Acid Soils," *R. I. Agric. Expt. Sta. Bul. 194.* 1923.

Johnson, M. O., "Manganese Chlorosis of Pineapples: Its Cause and Control," *Hawaii Agric. Expt. Sta. Bul. 52.* 1924.

Gile, P. L., and Carrero, J. O., "Cause of Lime-induced Chlorosis and the Availability of Iron in the Soil," *Jour. Agri. Resch.*, *20*, pp. 33-61. 1920.

Whiting, A. L., "A Biochemical Study of Nitrogen in Certain Legumes," *Ill. Agric. Expt. Sta. Bul. 179.* 1915.

Allison, R. V., Bryan, O. C., and Hunter, J. H., "The Stimulation of Plant Response on the Raw Peat Soils of the Florida Everglades through the Use of Copper Sulfate and Other Chemicals," *Florida Agric. Expt. Sta. Bul. 190.* 1927.

Graber, L. F., Nelson, N. T., Luekel, W. A., and Albert, W. B., "Organic

cies. The most common is possibly the lack of iron as evidenced by a chlorotic condition. This same condition (chlorosis) may also be caused by (or may indicate) an excess of manganese, poor drainage or lack of soil aeration, excessive potassium deficiency, excessive calcium supply, and various pathological conditions such as disease and insect attacks. On the other hand, there may be a soil deficiency that gives no visible sign in the crop itself, but when that crop is fed, may produce marked signs in the animal.

Food Reserves in Relation to the Growth of Alfalfa and Other Perennial Herbaceous Plants," *Wis. Agric. Expt. Sta. Resch. Bul. 80.* 1927.

Eckles, C. H., Becker, R. B., and Palmer, L. S., "A Mineral Deficiency in the Rations of Cattle," *Minn. Agric. Expt. Sta. Bul. 229.* 1926.

Elliott, W., *et al.*, "Investigation on the Mineral Content of Pasture Grass and Its Effect on Herbivora." A series of 5 papers, appearing in *Jour. Agric. Sci.*, *16*, Part 1. 1925.

Hart, E. B., *et al.*, "Phosphorus Deficiency and a Dairy Cattle Disease," *Wisc. Agric. Expt. Sta. Bul. 389.* 1927.

Alway, F. J., Shaw, W. M., and Methley, W. J., "Phosphoric Acid Content of Crops Grown upon Peat Soils as an Index of the Fertilization Received or Required." *Jour. Agric. Resch.*, *33*, pp. 701-740. 1926.

MacGillivray, J. H., "Effect of Phosphorus on the Composition of the Tomato Plant," *Jour. Agric. Resch.*, *34*, pp. 97-127. 1927.

PART IV

SOIL BIOLOGY

The soil may be considered a great reservoir from which all life springs and to which all life returns. No form of life is absolutely independent of it, and sooner or later all forms are incorporated within it. Plant life, from the highest to the lowest form, is rarely independent of the soil mass. It draws from that mass, and from the atmosphere above it, the inorganic nutrients needed for its existence and combines them into the life-giving food material. Animal life, in general, cannot assimilate inorganic materials, hence must feed, directly or indirectly, upon nutrients elaborated by plants.

The soil-plant relationship is mutual. Each exists for and each is benefited by the other. The life-giving plant materials ultimately become the life-giving materials of the soil mass. The biological processes and functions initiate and accelerate the ever-moving cycle of soil to plant and plant to soil.

CHAPTER 21

SOIL LIFE

Animal life is dependent for its existence upon plant life, and plant life in turn is dependent upon certain soil conditions. While animals may feed upon animals and, to a very limited extent, plants may live on plants, the action is not sufficiently complete to provide those soil conditions necessary for plant growth. This gap in the cycle from soil-derived plant food, through the plant and animal, to soil-derived plant food again, is filled by the action of micro-organisms. The statement is frequently made, "microscopic life is the connecting link between the kingdom of the living and the kingdom of the dead"; the assumption being, and correctly so, that present life exists on, and because of, the remains of past forms of life. This connective action is greater in the soil than in any other position in nature.

269. The Soil Population.—It is a well-known fact that the soil serves as a support and as a source of food supply for higher plant and animal life. These forms are complicated in structure and are usually of such size that they may readily be observed. But the earth is populated with a great group of living forms, simple in structure and usually microscopic in size. Some of these forms have all the characteristics of animals, others have the characteristics of plants, while a great number have some of the characteristics of both. The native home of many of these forms (excepting the aquatic) is in the soil. The majority of them do not require light for their growth, consequently they may live and function in the various soil horizons.

270. The Soil Fauna.—If we will carefully examine a number of soil masses, secured from various areas and horizons, we will find many living forms, some of which can be seen with the naked eye, others with a small hand-lens, while others will require the use of a high-powered microscope. Possibly the first form observed will be the common earthworm, *Oligochaeta terricolae,* whose life cycle is passed entirely within the soil. This

invertebrate is a member of the *Annelida* group, which may be represented by various other worms; for instance, small white worms of the family *Enchytraeidae* may be abundant in damp soil containing organic matter. Or one may observe snails, *Helicidae*, and slugs, *Liniacidae*, particularly the latter. Both of these regularly deposit their eggs in moist soil. Both forms belong to the group *Mollusca* and are included in the sub-order *Pulmonata* of the *Gastropoda*. Occasionally in the case of field soils, frequently in the case of garden soils, one will find a millipede, *Diploda*, or a centipede, *Chilopoda*, belonging to the group *Myriapoda*, or a few "wood-lice," "slaters," etc., of the order *Isopoda*, which are representatives of the group *Crustacea*.

The largest and most important group of soil invertebrates is undoubtedly that of the *Insecta*. Representatives of the *Diptera*, *Coleoptera*, *Hymenoptera*, and *Lepidoptera* may be found in all stages of development. Phytophagous species may be found on the subterranean parts of living plants, saprophagous forms on the dead material, and predaceous and parasitic forms preying on other members of the soil fauna. Some of these forms habitually live in the soil, while others may pass only certain stages in it. Some [1] of the forms may have little or no influence on the soil itself, others may affect it by influencing plant growth, while still others (for instance, the ant) may completely change the soil condition of a certain area **(84)**.

Many of the smaller members of these groups can only be seen by the aid of the hand-lens, which reveals also a new group of worms, the *Nematoda* or thread-worms. This group is well represented by the family *Anguillulidae*, or eel worms, numerous species of which form a definite constituent of the soil fauna. Some of them are free-living and non-parasitic; others, in particular *Heterodera radicicola*, are parasitic on a great number of plants, and may cause extensive crop losses **(324)**.

[1] For general reference, see:

Adams, C. C., "An Ecological Study of Prairie and Forest Invertebrates," *Bul. Ill. St. Lab. Nat. Hist.*, Vol. II, Article 2, pp. 33-264. 1915.

Cameron, A. E., "Insect Association of a Local Environmental Complex," *Trans Roy. Soc. Edinburgh*, *52*, pp. 37-78. 1917.

Morris, H. M., "Observations on the Insect Fauna of Permanent Pastures in Cheshire," *Ann. App. Biol.*, *7*, pp. 141-155. 1921.

Morris, H. M., "The Insect and Other Invertebrate Fauna of Arable Land at Rothamsted," *Ann. App. Biol.*, *9*, pp. 282-305. 1922.

McColloch, J. W., and Hayes, W. P., "The Reciprocal Relation of Soil and Insects," *Ecology*, *3*, pp. 288-301. 1922.

Even the simplest unicellular forms of animal life (the Protozoa) are represented in the soil fauna. The protozoa are divided into four main classes: (1) *Rhizopoda*, (2) *Mastigophora*, (3) *Ciliophora*, and (4) *Sporozoa*, only the first three of which are represented in the soil. The *Rhizopoda*, organisms whose organs of locomotion and food capture are pseudopodia, are represented by the *Amoebae* and the *Mycetozoa*. A member of the latter family is the familiar *Plasmodiophora brassica*, the organism causing the "finger and toe" disease of cruciferous plants. The *Mastigophora*, organisms possessing flagella, are represented by the *Flagellata* order. These organisms are mostly saprophytic in nature, some are able to ingest food particles, while others may utilize the energy of sunlight, thus functioning somewhat like the algae. The *Cilophora*, organisms moving by means of threads or cilia, have the largest number of representatives. This class feeds mainly by ingestion of the food particles. Some of this food is undoubtedly the other forms of microscopic soil life.

271. The Soil Flora.—The relationship existing between members of the plant kingdom and the soil is inseparable. This is especially true of the *Spermatophytes* or seed plants, the *Pteridophytes* or fern plants, the *Bryophytes* or moss plants, but not necessarily true of the *Thallophytes* or thallus plants. The first three groups may be considered as forming the basis or origin of the organic matter of the soil. The last group is the one that includes the microscopic forms of plant life, such as the algae, fungi, yeasts, and bacteria. With the exception of the algae, most of these forms are without chlorophyll. Some are able to use inorganic materials as a source of energy, but the majority are dependent upon the chlorophyllous plants for their food. From the standpoint of numbers, this group forms the largest percentage of the soil's population. From the standpoint of functions, it forms the main connecting link between the kingdom of the living and that of the dead, hence is possibly the most important of all soil groups. It is the group that by various processes decomposes the bodies of the higher plants and animals, returns them to the soil in their simplest combinations, and makes these combinations available for the use of plants as food. The different members of the group have decidedly different functions and produce decidedly different results, some of which may

be favorable to plant growth, some of which may be unfavorable, while others may have little or no influence. This group has been the basis for the development of soil microbiology.

272. The Development of Soil Microbiology.—Until the middle of the nineteenth century, practically nothing was known of microscopic life. The ancients had observed that organic matter, when added to the soil, gradually changed its form. It tended to disappear and left a dark-colored material, to which was given the name "humus" (225). In other words, the ancients were thoroughly acquainted with the *how* of decomposition, The *why* of decomposition and the birth of a conception of a microscopic soil population began with the celebrated researches of Pasteur (1822-1895), upon spontaneous generation and fermentation, and the development by Koch in 1881 of the gelatin-plate method for the isolation of pure cultures of bacteria.

In spite of the fact that it had not been seen, the presence of some form of microscopic life was suspected long before this time. The insistence of Liebig that plants took all of their nitrogen from the air in the form of ammonia, and the finding of plant physiologists that it was taken in the form of nitrates, did not agree. The views of the latter finally prevailed, but no one knew how the nitrates were formed. The first key to the situation was secured by Schloesing and Muntz in 1877, who allowed a stream of sewage water to trickle slowly over a column of sand and limestone. At first the ammonia in the sewage remained unchanged, later it was all changed to the nitrate. The process could be stopped with chloroform vapors or could be started by adding a little soil extract. The action of changing the ammonia to nitrates was attributed to "organized ferments." Others soon showed that this process could take place in the soil, and Warrington in 1881-82 proved that it took place in two stages, the ammonia being first converted to the nitrite and then to the nitrate, but failed to find the organisms concerned. The sudden and feverish interest taken in bacteriological soil investigations from this time forward is illustrated by the great number of investigations reviewed by Voorhees and Lipman,[2] who show that in spite of the newness of the science it is inseparably

[2] Voorhees, E. B., and Lipman, J. G., "A Review of Investigations in Soil Bacteriology," *U. S. Dept. of Agric. Office of Experiment Stations. Bul. 194*. 1907. 108 pp.

connected with the complex soil processes affecting plant growth. The most important work in the earlier development of the science is the solving of the problem of nitrogen fixation in the roots of legumes by Hellriegel and Wilfarth in 1886, the isolation of ammonia-oxidizing organisms on an organic-matter-free medium by Winogradsky in 1890, and the discovery of the nitrogen-fixing bacteria (*Azotobacter*) by Beijerinck in 1901.

273. The Population as a Basis for Grouping Soil Biological Studies.—The earlier biological investigations were made mainly by chemists and botanists. As the investigational phase of soils work has become more searching, the tendency is for an investigator to confine his attention more or less to one group of soil micro-organisms. Thus there are at present three well-defined lines of soil-microbiological investigations as follows:

I. Soil Bacteriology, broadly defined as a study of the character, life history, and functions of the micro-organisms living within the confines of the soil, and their relation to its crop-producing power. Soil bacteriological studies may be conducted along three well-defined lines. (1) They may consist of a study of the characteristics of one or more soil micro-organisms, using approved bacteriological methods. (2) They may consist of a study of the metabolic products and chemical function of one or more soil organisms using chemical methods. And (3) they may consist of a study of the biological life as a unit (no attention being paid to individuals or to groups) and the factors influencing it. For instance, some material may be added to a medium (usually soil), certain adjustments are made (water, temperature, etc.), and after or during a suitable incubation period, chemical measurements are made of certain involved changes. Or a suspension containing a unit of biological life is inoculated into a prepared medium (it may be of soil but is usually synthetic) and after a suitable incubation period, chemical measurements are made of the involved changes. During the earlier years, the majority of soil bacteriological studies were made on the basis of the biological life as a unit; consequently the separation of the various lines of studies are somewhat overlapping.

II. Soil Mycology, broadly defined as a study of the characteristics, life history, and functions of the different forms of fungi concerned in the transformation of materials used by plants as food. The studies are usually conducted in much the same manner

as described for soil bacteriology above. Soil mycology, except from the genetic standpoint, bears little relationship to the broader concepts of mycology. The mycologist and the plant pathologist are interested in forms producing a diseased condition in plants. The soil mycologist considers the chemical rather than the pathological function of the group.

III. Soil Protozoölogy, broadly defined as a study of the characteristics, life history, and functions of the different forms of protozoa living in the soil, their influence on the other soil micro-organisms, and their influence on materials used by plants as food. The studies may be conducted in much the same manner as described for soil bacteriology, but in this group a new biological factor is introduced, namely, the influence of one group on another. Many protozoal forms are able to ingest other and smaller organisms, thus by their activities changing more or less completely, the microscopic soil population.

The Microscopic Soil Population

The soil population may be considered from one of two viewpoints: first, the number and distribution of the various forms; and second, the activities and functions of the various forms as affecting plant growth. Let us consider the first view, reserving the second for discussion in the following chapters.

274. Number, Distribution, and Kind of Bacteria.—The number of bacteria in the soil mass is so large, while the organisms themselves are so small, that it is practically impossible to count them directly. The usual method is to make a soil suspension, dilute it to a known extent, and use a portion of the dilute as an inoculum for a prepared medium. The medium is usually plated. The number of organisms in the soil mass is calculated [3] from the average count of the numbers developing on the plates after a suitable period of incubation. While this method is open to the possibility of numerous errors and variations, it is valuable in that it gives a relative idea of the number of bacteria actually in the soil mass.

In general, it may be said that the number of organisms in a given soil mass is dependent upon the amount, condition, and

[3] Waksman, S. A., "Microbiological Analysis of Soil as an Index of Soil Fertility." 1. "The Mathematical Interpretation of Numbers of Micro-Organisms in the Soil," *Soil Science, 14,* pp. 81-101. 1922.

kind of food material in that mass, and the time of year the sample is taken (Figs. 23 and 24).[4] Sandy soils will often contain less than 100,000 bacteria per gram of air-dry material, while loams, having a high organic matter content, may contain many millions. The largest number are in the upper part of the soil horizon, usually in the portion subject to tillage operations. The number at the very surface may be relatively low, due to the germicidal action of sunlight and of drying. The number rapidly decreases with increase in depth. The rapidity of decrease depends upon the characteristics of the area. Usually humid soils contain very few bacteria below three feet, while arid[5] or more open-textured soils may contain an appreciable number at greater depths. In an alkaline soil, the number and activity of bacteria and other micro-organisms apparently vary with the kind and concentration of the alkali salt. Greaves[6] found that soils containing carbonates in abundance had the lowest total number of organisms, while soils containing sulfates in abundance had the largest total number of organisms.

Due to the fact that, under favorable conditions, the bacterial cell may multiply at a tremendous rate (a doubling of the number approximately every thirty minutes), or, under unfavorable conditions, may rapidly die off, there is a great variability in the number of bacteria in samples taken—first, from different positions in the same area; second, at different periods of the year; and, third, at different times of the day.

The bacterial content[7] of the soil consists primarily of non-spore-bearing bacteria (mostly immotile rods). Next to these in

[4] Erdman, L. W., "The Number of Micro-Organisms in Carrington Loam as Influenced by Different Soil Treatments," *Iowa Agric. Expt. Sta. Resch. Bul. 109.* 1928.

[5] Lipman, C. B., "The Distribution and Activities of Bacteria in Soils of Arid Region," *Univ. of Cal. Pub. in Agric. Sci., 1*, pp. 1-20. 1912.

[6] Greaves, J. E, "The Microflora and the Productivity of Leached and Non-leached Alkali Soil," *Soil Science, 23*, pp. 271-302. 1927.

[7] Conn, H. J., "Soil Flora Studies":

(1) "The General Characteristics of the Microscopic Flora of the Soil Part 1," *N. Y.* (Geneva) *Agric. Expt. Sta. Tech. Bul. 57.* 1917.

(2) "Methods Best Adapted to the Study of the Soil Flora. Part 2," *N. Y.* (Geneva) *Agric. Expt. Sta. Tech. Bul. 57.* 1917.

(3) "Spore-Forming Bacteria in the Soil," *N. Y.* (Geneva) *Agric. Expt. Sta. Tech. Bul. 58.* 1917.

(4) "Non-Spore-Forming Bacteria in the Soil," *ibid., Tech. Bul. 59.* 1917.

(5) "Actinomycetes in the Soil," *ibid., Tech. Bul. 60.* 1917. "The Punctiform-Colony-Forming Bacteria in Soil," *ibid., Tech. Bul. 115.* 1925. "The General Soil Flora," *ibid., Tech. Bul. 129.* 1927.

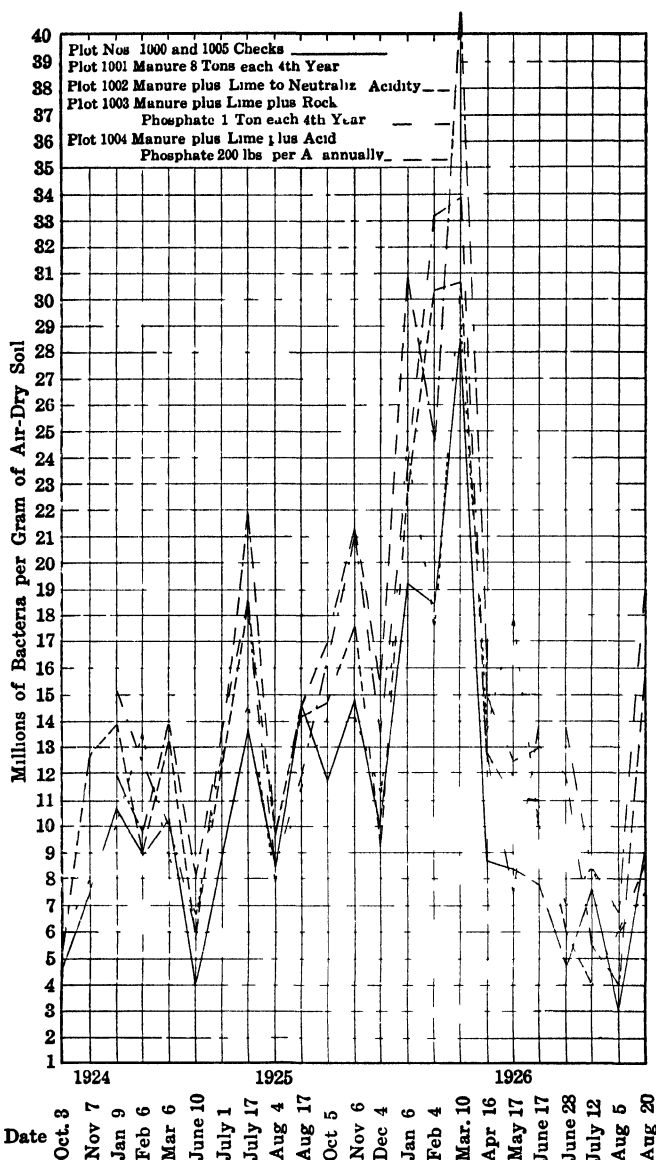



FIG 23—The number of bacteria in Carrington loam soil at different periods and the influence of different treatments

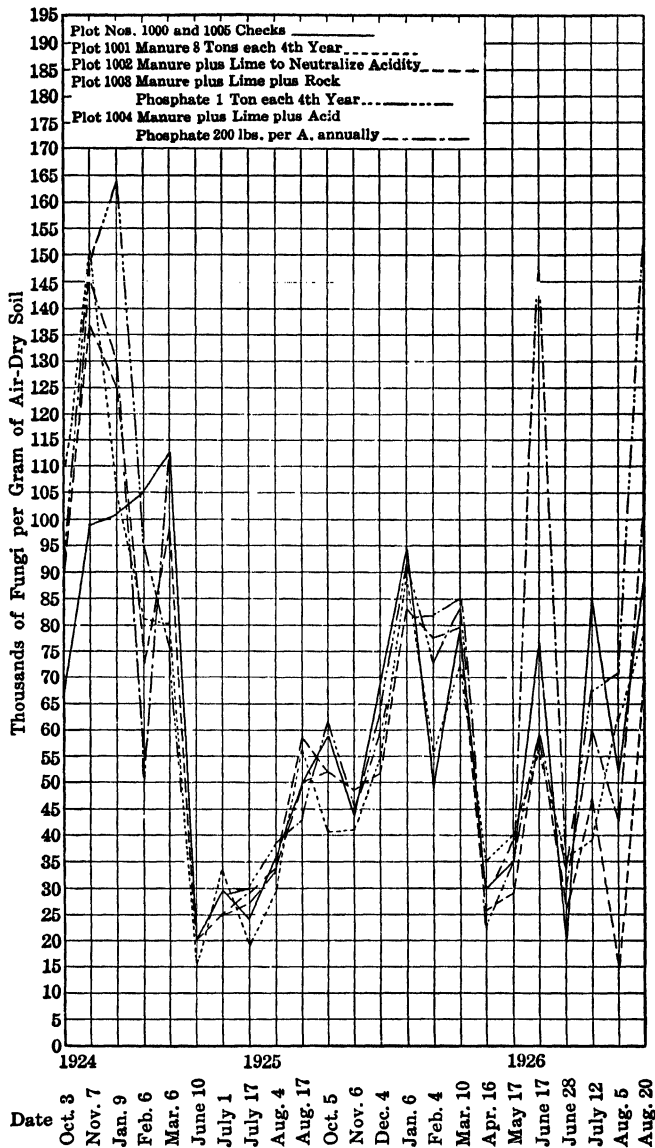



FIG. 24.—The number of fungi in Carrington loam soil at different periods and the influence of different treatments.

abundance are various types of *Actinomycetes* (thread-like bacteria). Certain spore-forming bacteria are also found. The latter are always present but in comparatively small numbers.

275. The Number, Distribution, and Kinds of Fungi.—The present knowledge of the soil fungi is extremely limited. This limitation is due mainly to the fact that adequate methods for their study have not been developed. Only certain forms can be detected by the methods now in use. These forms are limited to the filamentous fungi. The limitation is due, not to the inadequacy of the methods, but rather to the specific requirements of the individual forms for growth.

Usually the number of fungi is decidedly less than the bacterial content (from 1/10 to 1/100), depending upon the particular condition and the organic-matter content of the soil. Soils high in actively decomposing organic matter are usually high in number of fungi.

In comparison with numbers of bacteria or protozoa, the determination of numbers of fungi means very little. The organisms may be sterile in the soil, or form fruiting bodies consisting of few or many widely distributed spores. The spores are inactive, yet will appear as individuals on the plates and in the counts. The mycellial threads break into fragments that may grow and also be counted as individuals. In other words, the dilution method is satisfactory for separating the bacteria and protozoa but very unsatisfactory (yet at present necessary) for the isolation of the filamentous fungi. At present, there is no general method for the isolation and study of the fleshy fungi.

The distribution of the fungi appears to be governed by the same conditions as govern the distribution of the bacteria. The number rapidly decreases with increases in depth. The fungi apparently prefer a somewhat acid medium, consequently the reaction of the different horizons has a marked influence on their distribution.

The kind of fungi in the soil is problematical. Gilman and Abbott [8] describe 242 species, distributed in 61 genera, as normally occurring in the soil. All transitory forms, *i.e.* those possibly introduced by various methods or whose occurrence may in any way be questioned, were excluded. It is quite certain, however, that

[8] Gilman, J. C., and Abbott, E. V., "A Summary of the Soil Fungi," *Iowa Journal of Science*, *1*, pp. 225-343. 1927.

this list will be greatly enlarged. Comparatively little is known of the great groups of parasitic forms, of the fleshy forms, and of the soil algae.

While all fungi may be theoretically found in the soil, only a limited number are found in the natural state. Most of these are obligate saprophytes, though facultative parasites are found in large numbers where short rotations or single cropping systems favor the survival of the particular organisms. The list of fungi commonly found in forested soils, due to their undisturbed condition, acid reaction, and large supply of decomposable organic matter, is naturally much greater than in cultivated soils. Here one may find a wealth of the fleshy fungi.

276. Woody and Fleshy Fungi.—The woody and fleshy fungi are rarely found in cultivated soils, but usually are quite common in waste places, permanent pastures, lawns, around or in piles of decomposed materials, under buildings, etc., but more particularly in wooded and forested areas. Many of them are very small, with varying degrees of texture. Some are quite large and fleshy; some are edible. Some few are parasitic, some possibly symbiotic, but the majority are obligate saprophytes. Their principal activity is the decomposition of cellulose, and their beneficial activities in this direction may be said to be limited to new cut-over lands. The action of these fungi may be observed by examining an old stump or other wood material that is partially embedded in the soil. The characteristic fruit bodies are seen on the surface, while an examination below the surface will reveal large amounts of the white-colored mycelium[9] penetrating the tissues of the substratum on which it is feeding.

277. The Number, Distribution, and Kind of Protozoa.—The number of protozoa in the soil may be determined by the methods similar to the determination of the bacteria. In fact, the science of soil protozoölogy has developed as a result of biological (mainly bacteriological) studies, since 1910. The knowledge gained in a study of the activities of the bacterial and fungus forms appearing on plate cultures failed to explain many of the soil phenomena. Apparently there was a third biological group functioning in the soil that did not appear. The experiments of

[9] Shantz, H. L., and Piemeisel, R. L., "Fungus Fairy Rings in Eastern Colorado and Their Effect on Vegetation," *Jour. Agric. Resch.*, *11*, pp. 191-246. 1917.

Russell, Hutchinson, and their associates at Rothamsted (1909-1913) showed these functions [10] to be due to the rôle of protozoa in the soil.

Cutler (in Russell, pp. 66-98) shows the number of protozoa at Rothamsted (especially amoebae) to approximate the number of bacteria. The relationship was in inverse proportion and varied widely. A high active amoebae count was correlated with a fall in the numbers of bacteria, and vice versa. This was taken as an indication of the ingestion of the bacteria by the amoebae. In the United States, the number of protozoa appears to be much lower,[11] approximating 10,000 organisms per gram of fertile soil. Their distribution and variation is approximately the same as the bacteria.

The kinds of protozoa are apparently limited to the flagellate, cillate, and amoebae forms. These forms occur in two states, the active and the cyst. It appears that in field soils with a normal or even slightly supernormal moisture content, active protozoa [12] are not present, hence would not be a serious limiting factor in the soils of the United States. They are, however, active in soils containing a moisture content favorable for their development. This amount is usually decidedly above the average or optimum.

278. The Soil as a Biological Culture Medium.—The soil is both a home and a culture medium for many of the biological forms. One must not assume, however, that all organisms living in the soil are able to function to the same degree of efficiency. The variable physical and chemical functions have a marked bearing on the efficiency of the soil population. Thus we find one group preferring the lower, and another the upper, soil horizons. One group will function efficiently in a neutral soil and possibly not function at all in either an acid or an alkaline soil. Practically all the physical and chemical functions previously cited have an influence on the microscopic soil life. In other words, the soil

[10] Kopeloff, N., and Coleman, D. A., "A Review of Investigations in Soil Protozoa and Soil Sterilization," *Soil Science*, *3*, pp. 197-269. 1917.

Russell, E. J., *et al.*, *The Micro-Organic Population of the Soil.* Longmans Green and Co. London, 1923. 188 pp.

Sandon, H., *The Composition and Distribution of the Protozoan Fauna of the Soil.* Oliver and Boyd. London, 1927. 237 pp.

[11] Sherman, J. M., "Studies on Soil Protozoa and Their Relation to the Bacterial Flora." (1) *Jour. of Bacteriol.*, *1*, pp. 35-66 (1916); (2) *Jour. of Bacteriol.*, *1*, pp. 165-185 (1916).

[12] Koch, G. P., "Activity of Soil Protozoa," *Jour. Agric. Resch.*, *5*, pp. 477-488. 1915.

acts as a natural cultural medium (that possibly cannot be artificially duplicated) for the biological life within it, the life adjusting itself to, or being governed by, the condition of the mass. Naturally, the products of the activities of such a variable group of organisms have a variable influence upon the soil itself.

279. Approximate Mass of the Soil Population.—Löhnis and Fred [13] assume a soil population of one hundred million bacteria per gram of soil. The average size of these organisms is taken as one micron and the specific gravity as 1.0. Then the weight of one hundred million organisms is 1/10 milligram. The weight of one acre of soil to a depth of twelve inches is approximately 4,000,000 pounds. One 12-inch acre of soil, containing 100,000,000 bacteria per gram, would contain therefore approximately 350 pounds of living cells. If the bacterial population makes up from 50 to 75 per cent of the total mass (bacteria, fungi, algae, protozoa, etc.) then the total mass of the active micro-organic population would be approximately 525 to 700 pounds per acre. In other words, the weight of cattle kept on a pasture is approximately equal to the weight of the mass of living micro-organisms in the soil beneath.

280. Studies of the Micro-Organic Soil Population.—The earlier studies of soil micro-organisms were mainly concerned with the estimation of the number of bacteria and fungi. It was soon recognized that this information was altogether insufficient to allow an understanding of the direct relation of the soil flora to its crop-producing powers. The earlier studies were also concerned with the function of the organisms, that is, with their physiological activity in relation to plant life, in particular their relation to the nitrogen supply. As a result, two conceptions in microbiological soil investigations developed, one concerned primarily with numbers, the other with physiological activities. The greater development in soil investigations has been made along the latter line.

The number and variety of micro-organisms in the soil is so enormous and so variable that it is impracticable (in fact, due to limitations of present methods, impossible) to separate out all the different species and study their characteristics. In some cases, it is desirable to find the organism or organisms producing

[13] Löhnis, F., and Fred, E. B., *Textbook of Agricultural Bacteriology*, p. 60. McGraw-Hill Book Co. New York. 1923. 283 pp.

a certain chemical change. This is done by making conditions favorable for the group to be isolated, and thus by successive transfers (enrichment process [14]) encourage their growth to the exclusion of all others. But the morphology of many of the microscopic soil forms is not constant. A single species may exhibit a variety of forms under different temperatures or growing on different media. This is especially true in the case of the fungi, may or may not be true in the case of the bacteria, and possibly is not true in the case of the protozoa.[15]

At the present time, the American Society of Bacteriologists is standardizing the diagnostic characters used in describing bacteria, also the media and cultural conditions under which they are grown. This will ultimately lead to a better understanding of the functions of the species making up the soil flora.

[14] Gibbs, W. M., "The Isolation and Study of the Nitrifying Bacteria," *Soil Science*, 8, pp. 427-481. 1919.

[15] Löhnis, F., and Smith, N. R., "Life Cycles of the Bacteria," *Jour. Agric. Resch.*, 6, pp. 675-702 (1916) show that in a study of 42 strains of bacteria, all lived alternately in an organized and in an amorphous stage, the latter producing new individuals of varying forms.

CHAPTER 22

THE FUNCTION OF THE MICRO-ORGANIC SOIL POPULATION

The function of micro-organisms, particularly those constituting the soil population, are concerned mainly with the progression of the cycle of matter. The constructive work done by most of the higher organisms (that is, the accumulation and combination of elements into complex combinations forming the organism itself) is undone by the destructive (decomposition) work of the majority of the soil micro-organisms. In this connection, the soil micro-organisms act as saprophytes (feed on dead matter). They utilize (decompose) the carbonaceous material of organic matter and secure from it the energy necessary for their existence. In the process, they utilize mainly the protein (carbon, hydrogen, oxygen, and nitrogen) portion of the material and may or may not completely utilize the other elements.

Of course the soil is populated with many pathogenic forms (organisms living on, or parasiting, living matter). The action of these may be considered as representing a transgression of their proper domain because they usually hinder plant development, accelerate the time of death, and hasten decomposition. The function [1] of the soil micro-organisms cannot be viewed as always destructive. Some of them, particularly those fixing atmospheric nitrogen (**298**), oxidizing sulfur (**308**), etc., may do some very important and constructive work.

281. Physiological Functions.—The physiological functions of micro-organisms are concerned mainly with their food and

[1] For general reference, see:

Waksman, S. A., *Principles of Soil Microbiology*. Williams and Wilkins Co. Baltimore, Md., 1927. 897 pp.

Löhnis, F., and Fred, E. B., *Textbook of Agricultural Bacteriology*. McGraw-Hill Book Co. New York, 1923. 283 pp.

Greaves, J. E., *Agricultural Bacteriology*. Lea and Febiger. Philadelphia, 1922. 437 pp.

United States Dept. Agric. Library. Bibliog. Contrib. No. 13, pp. 289-363. Washington, 1927.

its use as building material and a source of energy. They require the same elements in somewhat the same varying proportions as the higher plants. Actually they utilize little of the organic material on which they feed; practically they destroy much. The amount utilized, due to the comparatively short span of life, may soon become subject to the attacks of other forms. It becomes evident, therefore, that from the standpoint of the plant-food elements in the soil, a study of the physiological functions of micro-organisms concerns not only the food required by the organisms themselves, but mainly the various biochemical changes produced in their metabolic processes.

282. Classification of Physiological Functions.—The substances produced in micro-biological metabolism, from a physiological viewpoint, are classified by Greaves [2] as follows:

I. The Secretions.—Enzymes and similar substances which serve some purposeful end in cell economy. Some of these may be retained within the cell (intracellular); others may pass out into the surrounding medium (extracellular).

II. The Excretions.—The waste products of cell metabolism, substances ejected because they are useless to the organism. The excretions of organisms, amoeba, etc., capable of ingesting their food.

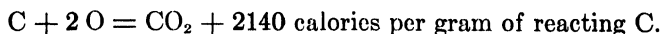
III. The Disintegration Products.—Substances produced by the breaking down of the food materials (decomposition). The nature of the substance is determined partly by the chemical structure of the nutrient, and partly by the specific organism concerned. In some cases, the environmental condition may be an important factor. The excretions and the disintegration products are closely allied.

IV. The Cell Itself.—The true cell substance (the cell composition) is variable [3] even in the same species, the variability being due mainly to the composition of the nutrient. Carbohydrates (celluloses, starches, and sugars, etc.) are mostly absent, being represented by chitin, albumin, glycogen, granulose, etc. Fatty and waxy substances may be present, especially in spores or resting forms. Water forms from 75 to 98 per cent of the vegetative cell and about 40 per cent of the spore. The mineral content of dried cells varies from 2 to 30 per cent, nitrogen content

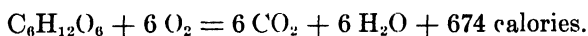
[2] *Agricultural Bacteriology*, p. 82.
[3] Löhnis and Fred, *Agricultural Bacteriology*, p. 40.

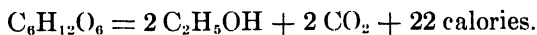
usually from 1 to 10 per cent, in some cases (organisms capable of assimilating atmospheric nitrogen) it may be approximately 50 per cent higher. While the ash content is quantitatively higher than that of higher plants, qualitatively it is composed of the same elements and in the same relative proportions.

283. Energy Relationships.—The soil organic matter is utilized by soil micro-organisms for two purposes: (1) the furnishing of energy, and (2) supplying materials for building the cell. The energy is secured by the oxidation of carbon **(259)**. This action may be illustrated by the following reaction:

$$C + 2\,O = CO_2 + 2140 \text{ calories per gram of reacting C.}$$

This is equivalent to saying that the energy in one gram of uncombined carbon and oxygen, mixed in the proportion of one atom of carbon to two atoms of oxygen, exceeds that in the resulting one gram of carbon dioxide by 2140 calories.

Native carbon is relatively insoluble, contains little of the other elements; consequently it does not make an assimilable food for micro-organisms. Carbohydrates, particularly the sugars, are quite soluble; are widely distributed in nature; and are one of the main sources of energy for micro-organisms. The amount of energy secured by the oxidation of one of the simpler sugars (glucose) is:

$$C_6H_{12}O_6 + 6\,O_2 = 6\,CO_2 + 6\,H_2O + 674 \text{ calories.}$$

The ability of micro-organisms to oxidize the various forms of carbon varies widely. It is possible for some organisms (for instance, certain yeasts) to complete the oxidation of glucose, but the majority of them can only partially decompose their food, thus leaving in it varying amounts of its energy. For instance, certain yeasts will only partially oxidize the carbon in glucose (or other carbohydrates), producing alcohol with the result,

$$C_6H_{12}O_6 = 2\,C_2H_5OH + 2\,CO_2 + 22 \text{ calories.}$$

Over ten times as much energy is secured from the same amount of carbon in the first case as is secured in the second case. The difference represents the difference in the physiological efficiency of the organisms concerned.

It must not be assumed that micro-organisms can thrive on pure carbohydrate material alone. The other elements must be present for growth. Frequently they may be present in such very

small amounts as to require very careful analytical methods to detect them. In some cases, certain of the elements must be present in relative abundance. In most cases, the presence of a certain amount of nitrogen is required, in very few cases it may be absent. In a few cases, the organisms may secure their energy by the oxidation of some substance other than carbon; for instance, the oxidation of sulfur **(308)**.

284. Metabolic Functions.—Micro-organisms, like the higher organisms, require their food in solution, and in a more or less simple form before it can be utilized. The animal body is sometimes likened to a tube. The food can enter the tube, but does not actually enter the body of the tube until it is in a condition to pass through the membranes of the assimilating portion. The food cannot pass through the assimilating membranes until it has been acted upon by the digestive ferments, broken down into simpler combinations and rendered soluble. Most micro-organisms are unable to ingest their food. They differ from the animal in the fact that they must digest their food while the food itself is surrounding (outside as opposed to inside) the animal body. In other words, if a man was forced to feed the same as the micro-organisms, he would submerge himself in the desired food in order to place himself in a position to assimilate it. The assimilation by micro-organisms cannot take place until the food has been acted upon by certain substances (produced by both forms of living organisms) that bring about the desired change. The changes vary with different species of micro-organisms. The sum of all these changes which the food undergoes, including the deterioration of the organism itself, is called metabolism. The metabolic function of micro-organisms therefore is concerned with more or less complete decomposition, the resolving of the complex compounds into their simpler forms or combinations.

285. Enzymes.[4]—The substances produced by living organisms to bring about the solubility of insoluble organic materials and render them capable of being assimilated, and thus useful in life processes, are called enzymes. Inorganic materials when dissolved in water ionize readily. Organic compounds, on the other

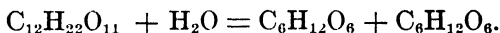
[4] For a complete discussion of enzymes, the student is referred to the excellent discussion of the subject presented by Waksman, S. A., *Enzymes*. Williams and Wilkins Co. Baltimore, Md., 1927. 1310 pp.

hand, ionize only very slowly. Enzymes (usually defined as "unorganized soluble ferments, elaborated by living organisms, whose activities are entirely independent of any of the life processes of the organism") act mainly by catalysis. They are capable of "altering the velocity of a chemical reaction without undergoing any apparent physical or chemical change themselves and without becoming a part of the product formed."

Enzymes are specific in their action. Any given enzyme affects only a single reaction, or at most acts only upon a single group of compounds which have a similar molecular configuration. Usually they are not active within the living microscopic cell, but become active by the presence in solution of other bodies. Their activity may be increased or retarded by other substances, salts, acids, temperature changes, poisons, etc., or by many varying conditions. Their chemical composition is in general unknown. They are destroyed by high temperatures, 80° to 100° C., and inhibited in action by low temperatures. The only test of their presence is by their activities. They are primarily colloidal in nature. Some function only in the cell of the organism (intracellular enzymes), while others are secreted (extracellular enzymes). The study of enzymes represents one of the most interesting and valuable chapters of biological functions.

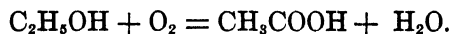
286. Classification of Enzymes.—From the general microbiological standpoint we may classify the activities of enzymes into four groups as follows:

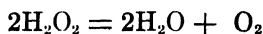
I. Hydrolytic.—Enzymes splitting carbohydrates, glucosides, fats, proteases, proteins, etc., mainly by the introduction of water (hydrolysis) into the molecule. The enzyme maltase converts maltose into dextrose and levulose as follows:

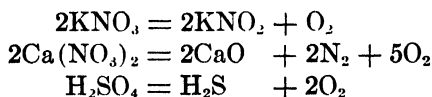
$$C_{12}H_{22}O_{11} + H_2O = C_6H_{12}O_6 + C_6H_{12}O_6.$$

II. Fermenting or Splitting.—Enzymes that accelerate fermentation or split the molecule. The enzyme zymase of yeast converts glucose into alcohol and carbon dioxide as follows:

$$C_6H_{12}O_6 = 2C_2H_5OH + 2CO_2.$$

III. Oxidizing.—Enzymes that accelerate oxidation. The oxidase of the acetic acid bacteria acting on alcohol is a familiar example:

$$C_2H_5OH + O_2 = CH_3COOH + H_2O.$$

IV. Reducing.—Enzymes that accelerate reduction, common in many forms of micro-organisms. One of the most important is the peroxidase which reduces hydrogen peroxide to water:

$$2H_2O_2 = 2H_2O + O_2$$

or the reduction of nitrates to nitrites or nitrogen, or of sulfates to sulfides:

$$2KNO_3 = 2KNO_2 + O_2$$
$$2Ca(NO_3)_2 = 2CaO + 2N_2 + 5O_2$$
$$H_2SO_4 = H_2S + 2O_2$$

287. Metabolic Products.—From the standpoint of soils we are mainly interested in those forms of microbiological functions affecting plant growth. It is well known that the process of decomposition of organic matter in the soil, with its resultant complex chemical changes, is controlled mainly by the activities of the micro-organic population. The decomposition of the remains of plants and animals in the soil is not accomplished by any one group. Apparently many groups of micro-organisms are concerned in the process, and the more resistant the tissues to rapid decomposition, the more complex the process becomes. At first the action is probably limited to a comparatively few forms, capable of destroying the wood-like portion of the tissues. The action is entirely biological, due to the efforts of the organism to digest the organic matter and thus secure the proper amount of food for its metabolic processes. But in the process of digestion the organism forms certain substances (metabolic products), for instance carbon dioxide, etc., that may cause an appreciable chemical reaction in the soil mass. As the digestive action continues, the complex organic molecules are subjected to the attacks of a greater variety of soil micro-organisms, and are split in various ways (Fig. 25), with the subsequent formation of literally hundreds of simpler chemical compounds. Some of these compounds may be in such form that they are capable of being assimilated by higher plants. Others may be in such a condition as to form an acceptable food for other micro-organisms. The process is one of reducing, step by step, the complex chemical composition of organic matter to its simplest combinations. During the process many compounds are formed that react with the insoluble materials of the soil mass. Thus the relatively insoluble mineral compounds may be rendered more soluble and

provisions made for a greater amount of available plant food in the soil mass.

288. Variations in the Metabolic Products.—The products of microbiological metabolism vary according to the physiological functions of the organism concerned; that is, their inherent ability to produce certain results under certain conditions. It also varies according to the age and species of the organism. Most important, it varies according to the presence or absence of oxygen.[5] In other words, the relation of the medium itself, in which the organism is functioning, has a marked influence on the kind of product. We may consider these variations from the standpoint of the decomposition of carbohydrates **(289)**, of protein **(293)**, and of the influence of various factors on the biological functions.

289. Carbohydrate Decomposition.—The decomposition of carbohydrates with its resultant products varies widely. It is affected by the kind of organism, the medium, and the oxygen relationships. It may be complete, *i.e.* the carbohydrate decomposed to carbon dioxide and water, or incomplete, *i.e.* the carbohydrate partially decomposed. The latter process is the most common for the majority of the soil micro-organisms. The following will serve to illustrate the various changes produced in the medium. Of course, in actual experience the reactions are not as simple as those written in the equations. Usually there are other products formed or the action is dependent upon the presence of certain mineral elements.

I. Hydration.—The natural carbohydrates are usually insoluble complex combinations of the simple sugars. These are reduced usually to a soluble state by hydration. Thus starch is hydrolized to maltose by the enzyme diastase or amylase, or cellulose is hydrolized to maltose by the enzyme cellulase, etc. Many forms of bacteria,[6] fungi, actinomycetes, etc., are concerned in the proc-

[5] The process of decomposition due to microbiological influence may be divided into three groups:

1. Fermentation, the decomposition of nitrogen-free organic compounds, chiefly carbohydrates.
2. Putrefaction, the decomposition of nitrogenous organic matter in the absence (or a limited supply) of oxygen.
3. Decay, the decomposition of nitrogenous organic matter in the presence of oxygen.

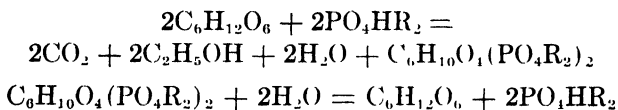
[6] McBeth, I. G., "Studies in the Decomposition of Cellulose in Soils," *Soil Science, 1*, pp. 437-487. 1916.

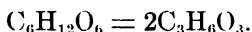
ess. Some of these forms may use the products of their metabolic functions, others are unable to carry the process further.

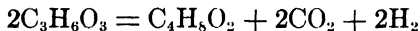
II. Oxidation.—The process of carbon (carbohydrate) oxidation is rarely completed by any one group of soil micro-organisms. The oxygen involved in the process may be secured from the air (aerobic process) or it may, in the absence of air (anaerobic process), be taken from the carbohydrate molecule itself. The processes of oxidation of direct importance in the soil are best illustrated from the standpoint of fermentation and acid production.

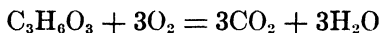
290. Fermentation.—Fermentation is mainly confined to the yeast group. The action in the case of yeast is apparently dependent upon a readily available supply of phosphate, which forms an intermediate product with the glucose:

$$2C_6H_{12}O_6 + 2PO_4HR_2 =$$
$$2CO_2 + 2C_2H_5OH + 2H_2O + C_6H_{10}O_4(PO_4R_2)_2$$

$$C_6H_{10}O_4(PO_4R_2)_2 + 2H_2O = C_6H_{12}O_6 + 2PO_4HR_2$$

291. Acid Production.—Acid production usually results from an oxidation of the alcohol produced in the fermenting process. This power is possessed by *Bact. aceti*, *Bact. pasteurianum*, and many other organisms. In many cases the organisms are able to hydrolize and decompose the carbohydrates into acids directly; for instance, *Streptococcus lacticus* hydrolizes lactose, $C_{12}H_{22}O_{11}$, to dextrose and galactose, then decomposes the hexoses to two molecules of lactic acid,

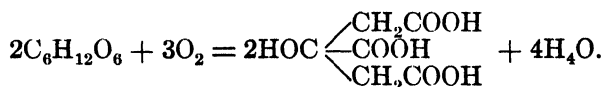
$$C_6H_{12}O_6 = 2C_3H_6O_3.$$

Under certain conditions the lactic acid is further changed into buteric acid,

$$2C_3H_6O_3 = C_4H_8O_2 + 2CO_2 + 2H_2$$

or the lactic acid may be completely oxidized to carbon dioxide and water.

$$C_3H_6O_3 + 3O_2 = 3CO_2 + 3H_2O$$

The buteric acid may be formed directly from the hexose,

$$C_6H_{12}O_6 + O_2 = CH_3CH_2CH_2COOH + 2CO_2 + 2H_2O.$$

Or the hexose may be decomposed with the formation of citric acid,

$$2C_6H_{12}O_6 + 3O_2 = 2HOC\begin{cases} CH_2COOH \\ COOH \\ CH_2COOH \end{cases} + 4H_4O.$$

In like manner, oxalic, formic, valeric, and many other organic acids may be formed. These acids usually do not remain in the soil as such but are attacked by the same or other groups. The result is the more or less complete decomposition of the carbohydrate into carbon dioxide and water.

The decomposition of carbohydrates by the complex soil population produces a wide and complex variety of products that are continually changing their form until the simplest combination (end-point) is reached. Usually the organism concerned is not characterized by producing a specific end-product, as in the case of the industries. A certain species may produce a variety of products; for instance, one important soil organism *Azotobacter chroococcum* produces in variable quantities from certain soluble carbohydrates: ethyl alcohol, glycocoll, acetic acid, butyric acid, lactic acid, carbon dioxide, and hydrogen.

292. Plant Food Relationships of Micro-organisms.—It cannot be assumed that the decomposition of a pure carbohydrate can be accomplished by micro-organisms in general. All life requires a certain balanced food, involving usually the ten [7] or more essential elements. Naturally micro-organisms require the presence of the mineral elements. The amount required may be in some cases extremely small. Apparently the various elements play rôles similar to that in the life of the higher plants. This statement applies particularly to the elements always occurring in the solid (non-volatile) state, namely, calcium, magnesium, phosphorus, etc., but does not necessarily apply to the elements that may occur in the gaseous (volatile) state, namely, carbon, hydrogen, oxygen, nitrogen, and sulfur.

The elements occurring as solids are used in varying amounts. Phosphorus is utilized by all micro-organisms in the building up of nucleoproteins and phosphoproteins. Some organisms apparently can assimilate either the organic or inorganic forms. Potassium, calcium, magnesium, and iron, while essential are usually required in very small amounts. Other inorganic constituents may be required, but the amount is usually so small that it is obtained either from the organic or inorganic source.

[7] A synthetic medium invariably contains ten or more elements.

The elements that may occur as gases play an entirely different rôle in micro-organic metabolism than they do in plant metabolism. Carbon may in some cases be taken from the atmosphere mainly as carbon dioxide, sometimes as carbon monoxide or as methane. In some cases the inorganic carbonates may be utilized. In the majority of cases micro-organisms cannot utilize the atmospheric forms of carbon but must secure their growth energy from various stages in the decomposition of carbonaceous materials. Hydrogen is usually obtained from organic compounds. Oxygen is required by all forms, but is secured in different ways. One group requires that their oxygen be furnished free, that is, atmospheric; to these is given the name "aerobic." Another group requires their oxygen in the combined form, not atmospheric; to these is given the name "anaerobic." If the organisms are absolute in their requirements (not able to encroach upon the domain of the other), they are known as "obligative." Some groups are not selective and are known as "facultative." Thus we have facultative or obligative anaerobes, or aerobes according to the individual preferences of the particular micro-organism.

The greatest distinction between plant and micro-organic metabolism is in the case of sulfur and nitrogen, particularly the latter. Sulfur is required by all micro-organisms, possibly in connection with the formation of protein. In addition some organisms may use it as a source of energy (283). Some organisms may utilize free elemental sulfur, others may utilize sulfates, sulfites, thiosulfates, or secure it from the protein of decomposing organic matter. Nitrogen is also essential. It is of primary importance in the soil due to the great variety of forms in which it is assimilated and the ease by which it may be leached or lost as a gas. Plants assimilate nitrogen primarily as the nitrate, sometimes as ammonia, rarely as any other form. The nitrates and the ammonia are secured entirely from the soil mass. Micro-organisms may assimilate the various inorganic and organic forms, except possibly the complex proteins. In addition some forms have the ability to take their nitrogen from the atmosphere and thus actually increase the amount in the soil.

293. Protein Decomposition.—Organic matter is a complex combination of the various plant-food elements. The three elements, carbon, hydrogen, and oxygen, make up the greater portion of the plant. These elements are combined in such combina-

tions as the simple sugars, the combined sugars, the starches, fats, oils, waxes, etc. These combinations may occur in pure form (carbohydrates) in some portion of the original organism, but that organism always contains in its entirety a certain amount of the soil-derived plant elements. Apparently the function of the soil micro-organisms in decomposing organic matter is practically as dependent upon the presence of the latter elements in organic matter as it is dependent upon the carbohydrate portion. These elements appear to act; first, as essentials in the life processes of the micro-organisms; second, as condiments, *i.e.* as materials to make the organic matter more acceptable to the micro-organism, and third, as a stimulant of a certain action; for instance, the presence of a small amount of nitrogen frequently stimulates the nitrogen-fixing bacteria to greater efforts.

In the process of decomposition, micro-organisms use excessive amounts of the elements carbon, hydrogen, and oxygen, but rather insignificant amounts of the other elements. As a consequence the process may be accompanied by the splitting off of many combinations which if not utilized by higher plants may be lost from the soil by leaching. The process is similar to that of digestion in the human body. That is, the organism secures its energy from the carbohydrate portion of the diet. In the absence of available carbohydrates the organism will utilize the carbonaceous portion of the protein compounds. Usually there is a large amount of material that cannot be utilized, hence occurs as waste. But the organism requires carbon for its energy relationships and all of the plant-food elements for its metabolic processes. We know that organic matter usually contains most, if not all, of the plant-food elements; it may or may not contain the utilizable carbohydrates (sugars). The soil micro-organisms are only dependent on the organic matter for their carbohydrate supply; the other elements are usually present in sufficient amounts, or if not, may be secured from the soil mass. Consequently the decomposition of organic matter in the soil is controlled mainly by the condition (relative solubility) of the material itself.

Assuming that utilizable carbohydrates are present in the decomposable organic matter, these will be attacked and used as a source of energy. The more complex organic molecules, carbohydrates and proteins, even though they are utilizable, will be

but slightly attacked. Micro-organisms show a marked preference for the simpler carbon compounds. The protein molecule may be attacked to secure from it the small amount of nitrogen and other elements needed in metabolic functions. In this case the waste products from the decomposition of the protein molecule may be comparatively small. If, however, the simpler carbohydrates have been utilized or are not present, the majority of the soil micro-organisms will attack and decompose the complex protein molecule. The molecule is hydrolized primarily for its carbon content and secondarily for its nitrogen content or the other elements it may contain. The carbohydrate portion is utilized rapidly, the other elements are utilized in small amounts; consequently they tend to accumulate as waste products.

It apparently makes little difference whether the decomposition of protein takes place in the presence or the absence of oxygen; the end-products are approximately the same, but the intermediate products may markedly differ, being mainly oxidized or unoxidized according to the air supply. The organic matter is gradually and in time completely decomposed, with the formation of many intermediate products (most of which are acidic in reaction) and with the formation of end-products most of which are either alkaline or neutral in reaction.[8] This point is graphically illustrated in Fig 25. In reality, complete decomposition is the same as complete ignition; the only difference is in the time involved. The non-volatile portion of the organic matter is split off as the base which combines with the most available acid to form a salt which is usually neutral. Thus Ca, Mg, K, etc., may combine with (HCO_3), CO_2, SO_4, PO_4, etc., for instance, calcium nitrate.

The end-products of the volatile portion are of decided importance from the standpoint of plant food because of the fact that not only may they be decomposed to simple compounds, but they may also be liberated as gases. The carbohydrate portion ends mainly in carbon dioxide and water, thus giving rise to the important chemical effects of carbonation (207). The sulfur may finally split off as the element sulfur; as sulfite, sulfate, or thiosulfate salts; or as the gaseous hydrogen sulfide. Nitrogen is split off from native proteins, first in such combinations as

[8] Schreiner, O., "Changes in Character, Condition, and Amount of Soil Organic Matter," *Jour. Amer. Soc. Agron.*, *18*, pp. 115-126. 1926.

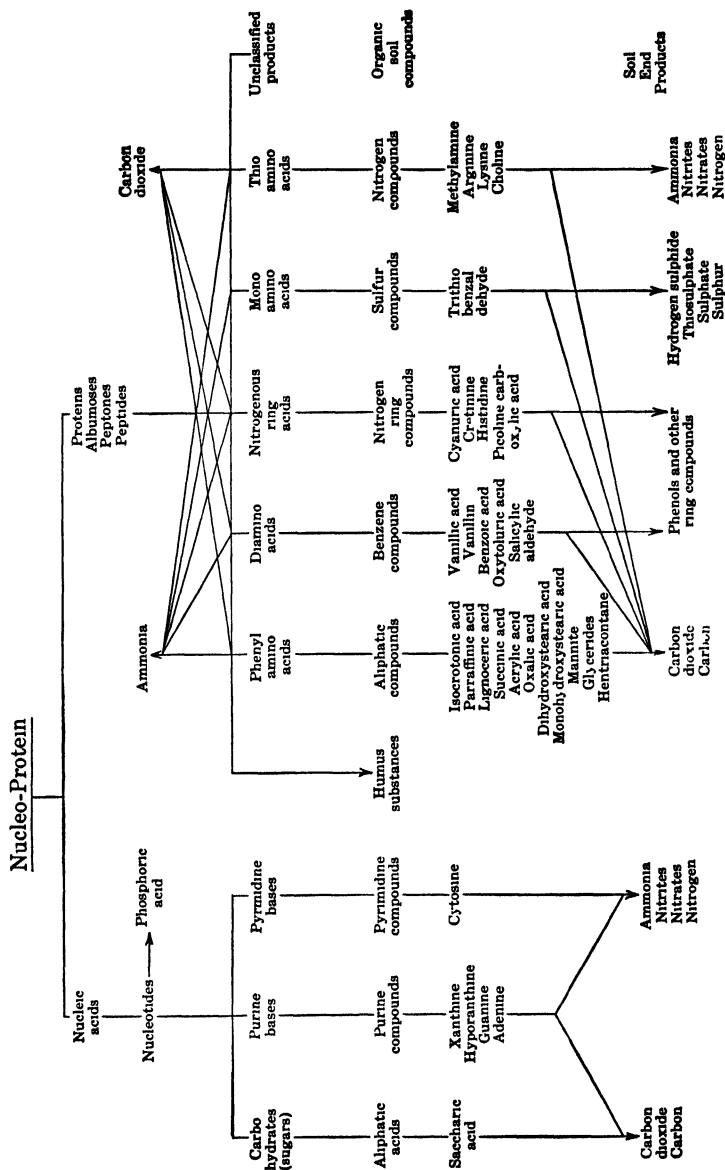
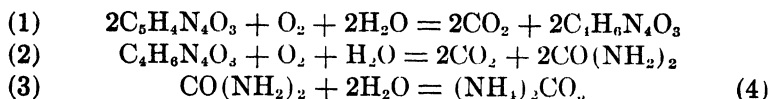



Fig 25—Illustrating changes in soil organic matter.

proteoses, peptones, polypeptids, peptids, and amino acids. The amino acids are easily split with the formation of ammonia. This stage in the transformation of nitrogen in the protein molecule is accomplished by the majority of the soil micro-organisms. The ammonia may form ammonium salts, it may be absorbed or adsorbed by the soil mass, or it may be lost as a gas. The process of ammonia formation is the regular course of the nitrogen cycle, and the end-product (ammonia) apparently is the same, regardless of the decomposition conditions. The process has been the subject of extended investigations and is usually referred to as "ammonification" (295).

294. Biological Processes Concerned with Nitrogen Transformation.—As the question of the nitrogen supply has been paramount in the history of soil investigations, and as nitrogen transformations are a direct result of microbiological activities,[9] it is but natural that the majority of research workers have confined their attention to some phase of the nitrogen problem, for instance, ammonification, nitrification, denitrification, and nitrogen-fixation.

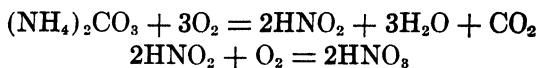
295. Ammonification.—Ammonification is the production of ammonia by the hydrolysis and reduction of protein compounds in order that growth energy may be secured and the essential elements assimilated by the decomposing organism. The reactions involved may be represented by the decomposition of uric acid (1), which is changed to allantoin (2), then to urea (3), and finally to ammonium carbonate (4):

$$(1)\quad 2C_5H_4N_4O_3 + O_2 + 2H_2O = 2CO_2 + 2C_4H_6N_4O_3$$
$$(2)\quad C_4H_6N_4O_3 + O_2 + H_2O = 2CO_2 + 2CO(NH_2)_2$$
$$(3)\quad CO(NH_2)_2 + 2H_2O = (NH_4)_2CO_3 \quad (4)$$

This process results from the activity of the majority of the micro-organisms comprising the soil population. It may be said that practically all soil micro-organisms are more or less active ammonifiers.

296. Nitrification.—Is the oxidation of ammonia to nitrites and nitrates. From the broader standpoint the term is often used to imply the production of nitrates from decomposing organic

[9] Evidence has been introduced to show that plants may in the seedling stage fix atmospheric nitrogen. See Lipman, C. B., and Taylor, "Proof of the Power of the Wheat Plant to Fix Atmospheric Nitrogen," *Science*, 56, p. 605. 1922.

matter. Consequently ammonification may be regarded as the primary step in nitrification, while nitrification itself is the final step in the mineralization of nitrogen compounds. The reactions involved may be represented by the oxidation of the nitrogen in two stages,[10] first to nitrite and then to nitrate:

$$(NH_4)_2CO_3 + 3O_2 = 2HNO_2 + 3H_2O + CO_2$$
$$2HNO_2 + O_2 = 2HNO_3$$

The action has been attributed to two groups of organisms, the nitrite-formers being called *nitrosomonas* and the nitrate-formers *nitrosococcus*. A third group, *nitrobacter,* is assumed to be able to oxidize the ammonia directly to the nitrate. The action was assumed for a long time to take place only in the absence of decomposable organic matter. Later work,[11] however, has shown that the whole subject of the metabolism of nitrifiers is indefinite and that the process is very complex. The fact remains, however, that as far as is known the process is biological rather than chemical in nature and usually is one of the controlling factors in crop production. It is markedly influenced by the reaction of the soil and takes place independent of higher plants. Usually the supply of nitrate nitrogen in the soil is limited, however; conditions may arise where the concentration may be such as to prove toxic to plant growth **(247)**.

297. Denitrification.—Denitrification is a more or less indefinite term to describe the loss of nitrogen from a medium, excepting those losses that may be accounted for; for instance, leaching, removal by crops, etc. It involves mainly the reduction of nitrogen compounds to elemental nitrogen and usually takes place under anaerobic conditions. While many of the soil micro-organisms may be concerned in the process, the reactions involved may be strictly chemical as well as biological. For instance, the presence of easily oxidizable substances may participate in nitrate reduction—chemical,

$$5C_6H_{12}O_6 + 24KNO_3 = 24KHCO_3 + 6CO_2 + 18H_2O + 12N_2$$

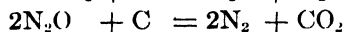
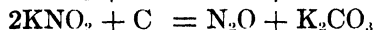
[10] Winogradsky and Omelianski, *Cent. f. Bakt. Abt.* 2. 5, pp. 388 f. 1899.

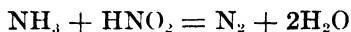
[11] Gibbs, W. M., "The Isolation and Study of the Nitrifying Bacteria," *Soil Science*, 8, pp. 427-481. 1919.

Gowda, R. N., "Nitrification and the Nitrifying Organism," *Jour. Bact.*, 9, pp. 251-272. 1924.

Gowda, R. N., "Oxidation of Ammonia and Nitrites by Micro-Organisms under Different Conditions," *Soil Science*, *17*, pp. 57-64. 1924.

or microbiological activity—biological,

$$2KNO_3 + 2C = N_2O + K_2CO_3 + CO_2$$
$$2KNO_2 + C = N_2O + K_2CO_3$$
$$2N_2O + C = 2N_2 + CO_2$$

or the splitting off of nitrogen by the action of nitrous acid on ammonia or on amines:

$$NH_3 + HNO_2 = N_2 + 2H_2O$$
$$CH_3NH_2 + HNO_2 = N_2 + CH_3OH + H_2O$$

298. Nitrogen Fixation.—This is the assimilation of free nitrogen by certain bacteria, fungi, and algae. In some cases the nitrogen is fixed when the organism is living in symbiosis with another organism **(314)**. In other cases the nitrogen is fixed as a part of the metabolic functions of certain organisms, possibly in decomposing organic matter. The latter process is usually spoken of as non-symbiotic nitrogen fixation, or by some as azofication.[12]

The power of non-symbiotic nitrogen fixation is limited mainly to the algae and certain bacteria. Of the many different bacterial forms there are two that are important, both from the standpoint of their ability to increase the nitrogen supply of the soil mass and from the standpoint of their wide distribution. These two forms may be represented by *Azotobacter chroococcum* as a type of the aerobic organism, and by *Clostridium pasteurianum* as a type of the anaerobic organism.

The amount of nitrogen fixed depends upon the efficiency of the organism, the composition of the medium and its reaction, the availability of the carbohydrate, and the time required. An average of 10 milligrams of nitrogen may be fixed by *A. chroococcum* from one gram of mannite in 10 days. Dextrose is usually about one-half as efficient, while humus is approximately one-tenth as efficient as mannite.

Little is known of the reactions involved in nitrogen fixation. Apparently the nitrogen (regardless of the form on entering the cell) is rapidly converted by the metabolic processes into complex proteins.

299. General Classification of Microbiological Functions.—There is apparently no accepted classification of microbio-

[12] For an excellent summary and discussion of non-symbiotic nitrogen fixation see Greaves, J. E., "Azofication," *Soil Science*, 6, pp. 163-217. 1918.

logical functions. The earlier workers tended to speak of the process of ammonia production as "ammonification," the process of sulfur oxidation as "sulfofication," etc. If the process was reversed the reversal was indicated by the prefix *de*. Thus the terms nitrification, denitrification, etc., came into general use. These terms[13] are usually derived in part from the Latin word *facio* ("make"), to which a word descriptive of the process is prefixed. The terms are somewhat loosely and often incorrectly used. Sometimes the term "nitrification" includes both ammonification and nitrogen fixation, or "denitrification" is confused with nitrate reduction or nitrogen assimilation. In some cases the meaning implies a process (chiefly oxidative), in others it implies an end-product (as in ammonification), while the term "azofication" refers to a process of biological assimilation. Many similar terms have been used.

300. Chemical Classification of Microbiological Functions. —From the foregoing it is apparent that the decomposition of organic matter in the soil mass (with its attendant influence on the crop-producing powers) is dependent upon the activity of its microbiologic functions but that the sum of the reactions involved is not entirely biological. In fact, the micro-organisms are in reality the instigators and accelerators of the various chemical actions and reactions, which, when well started, may proceed to some extent without them. For instance, a sterilized soil mass may continue to give off measurable amounts of carbon dioxide for an appreciable period after sterilization, or the action accomplished by enzymatic processes, when well started, may proceed independently of the organism according to the presence or absence of certain factors—for instance, the removal of the end-products.

The classification of the functions of micro-organisms does not explain the chemical actions involved, neither does it correlate the biological function with the different soil elements used as food by the soil population. Emerson[14] suggests a classification designed to correlate the chemical processes of biological metabolism with the terms usually used in describing the func-

[13] Lipman, J. G., "Suggestions Concerning the Terminology of Soil Bacteria," *Botanical Gazette*, *51*, pp. 451-460. 1911.

[14] Emerson, Paul, "A Chemical Classification of the Activities of Soil Micro-Organisms," *Iowa Academy of Science, Proceedings*, *29*, pp. 355-359. 1922.

tions of soil micro-organisms, as follows, the element carbon representing the gaseous elements and the element sulfur the mineral elements:

Digestion

Largely hydrolytic, rendering insoluble compounds soluble. Primarily extracellular. Slight changes in energy relationships. May be anaerobic or aerobic.

Carbon: Hydrolytic splitting (the hydrolysis of starch) no term for designation of the microbiological action involved.

Nitrogen: Splitting of higher nitrogen-containing compounds with the formation of peptoses, etc., amino acids, and finally ammonia as an end-product. Microbiological term. Ammonification.

Sulfur: Splitting of organic sulfur compounds with the formation of hydrogen sulfide as the end-product. No term for designation of the microbiological action involved.

Assimilation

Elements or compounds taken into the cell and there built up into protoplasm, cell walls, etc. Intracellular action, possibly the result of extracellular enzymatic action.

Carbon: Usually involves dehydration, may also involve reduction (sugars to carbon dioxide). No term for designation of microbiologic action.

Nitrogen:

1. The assimilation of nitrogen compounds. No term for designation of microbiologic action.
2. The assimilation of atmospheric nitrogen.
   - (a) By bacterial action
     - (1) By aid of plants. Microbiological term for designation of action, "symbiotic nitrogen fixation," sometimes "rhizofication."[15]
     - (2) By bacteria alone. Microbiological term for designation of action, "non-symbiotic nitrogen fixation" or "azofication" or sometimes "azotofication."
   - (b) By other organisms; plants, yeasts, algae, etc. Usually the action is designated as "the nitrogen-fixing power." No specific term.

Sulfur: The assimilation of sulfur compounds. No term for designation of microbiologic action.

[15] This term does not appear to any extent in the literature but has been used exensively in the soil bacteriology lectures at Iowa State College. See Brown, P. E., "The Teaching of Soil Bacteriology," *Amer. Soc. Agron., 13*, pp. 323-329. 1921. As the real meaning of the term is root-making, it has no place in a classification of microbiologic functions.

OXIDATION

Elements or compounds oxidized partially or completely in order to secure growth energy. Action usually intracellular.

Carbon: Action as above. No term for designation of microbiologic action.

Nitrogen: Ammonia or ammonium compounds oxidized to oxides of nitrogen, to nitrites, to nitrates, by various stages or directly in order to secure growth energy, usually for the assimilation of carbon dioxide. Microbiological term for designation of action, "nitrification."

Sulfur: Free sulfur or hydrogen sulfide oxidized to sulfites or sulfates. Microbiological term for designation of action, "sulfofication."

REDUCTION

Aerobic or anaerobic processes by which compounds are reduced to furnish oxygen.

Carbon: Occasionally a part of assimilation; part of the carbon may be reduced while another part is oxidized. No term for designation of microbiologic action.

Nitrogen: Primarily anaerobic. End-products, reduced nitrogen compounds or free nitrogen. Microbiological term, "denitrification, deazofication, or deazotofication."

Sulfur: The reduction of sulfates and sulfites. Microbiological term, "desulfofication."

301. The Decomposition of Micro-organisms.—There is no question regarding the ability of microscopic life to decompose the remains of higher plants. Further, many of them apparently have the power to decompose the remains of other micro-organisms. It is well known that many forms of organic matter will, if protected from microbiological attacks, retain their original structure for long periods (wooden structures). In other words, the higher organisms of plant life possess no equipment for the decomposition of their bodies. Apparently the microscopic cell possesses something that, when life-processes cease, will decompose or destroy the cell. The process is called "autolysis" (self-digestion). Little is known regarding it except that a dissolving or disintegration process takes place. The disintegration process, however, may or may not mean the death and decomposition of the organism. It is claimed that in many cases a breaking down of the cell structure is merely a natural life phase. The stage of

disintegration or of amorphous products[16] is called the "symplastic" stage. From this stage minute globoid bodies, either of themselves or by coalescing with other bodies (the individual units being called "regenerative units") form the basis for the growth and reproduction of new cells.

[16] Löhnis, F., and Smith, N. R., "Life Cycles of the Bacteria," *Jour. Agric. Resch.*, 6, pp. 675-702. 1916.

CHAPTER 23

FACTORS INFLUENCING THE BIOLOGICAL FUNCTIONS IN SOILS

The ability of all living forms to utilize their food depends to a certain degree on their environmental condition. In the case of the higher organisms, the environment does not have the marked effect on animals that it has on plants. In the case of micro-organisms the environment is possibly the most important of all factors. This is due to the fact that the ability of a certain kind of micro-organism to utilize its food depends on the physical and chemical condition of its environment. Thus we find that such factors as moisture, temperature, light, air, reaction, food supply, and biological relationships are of great importance. The sum of these environmental factors governs the kinds of organisms functioning and the various products formed. Wide variations of temperature, slight or excessive amounts of water, variations in the depth of the soil mass, etc., may, even in the presence of such a complex mixture as the soil's population **(269)**, cause variable results from the standpoint of changing the condition of food available for plants. If a certain environmental condition predominates, this factor may favor the growth of certain organisms, hence govern the kind of products formed.

302. Water.—Most organisms (consisting as they do of 75 to 98 per cent water) are little more than naked masses of protoplasm. The cell wall of active forms is entirely too delicate to resist desiccation, consequently it may be said that "microbiologic life functions only in solution." Any interference with the amount of water normally present causes a change in the activity of the cell. Rapid changes usually cause death, while slow changes may, in the case of a reduction of moisture, bring about in certain forms a condition of metamorphosis, a resistant condition (spore, cyst, etc.) on the part of the organism. In this resistant state the organism is inactive.

Water is essential not only from the environmental standpoint

but from every phase affecting life processes. It is essential in all chemical reactions, it is assimilated in hydration, split off in synthesis, and acts as a solvent and carrier for the various products. The functions of micro-organisms are affected by the concentration and character of the solution in which they are living. The organism must feed by a process analogous to osmosis, consequently pure water or a dilute solution may cause swelling (plasmoptysis if the change is rapid) of the cell, while a concentrated solution will cause a shrinking (plasmolysis if the shrinking results more or less in collapse). If the changes are slow the micro-organisms may gradually adapt themselves to a condition that would prove fatal otherwise. In fact they may survive and even develop in solutions whose concentration[1] would be fatal to higher plants or other microscopic forms. For instance, many of the soil bacteria and fungi have the ability to grow in relatively highly concentrated salt or sugar solutions.

The air-water balance **(118)**, the maintenance of which is so essential in the case of higher organisms, is to a certain degree of equal importance in the functioning of those micro-organisms beneficial to plant life. The majority of the beneficial soil micro-organisms are aërobic and their oxidized products are beneficial to the chlorophyllous plants. Their functions are controlled by the same maximum and minimum soil water-content **(185)** as plants. An excess of water provides conditions favorable for the anaerobic organisms, protozoa, etc., that may cause a serious depletion of the nitrogen supply either by denitrification **(297)** or by direct removal and utilization. An excess of water may also cause the formation of substances that would hinder further decomposition. An illustration of the latter action is the formation of peat beds.

A lack of water (drought) does not terminate microbiological life as quickly as it does higher plants. A slowly diminishing water supply apparently stimulates the organism to meet the change in environmental conditions. Many are enabled to form spores, etc., others apparently are protected by a mass of gelatinous material surrounding the cell. Furthermore, soil that is apparently dry still contains appreciable amounts of hygroscopic

[1] Millar, C. E., "Relation between Biological Activities in the Presence of Various Salts and the Concentration of the Soil Solution in Different Classes of Soil," *Jour. Agric. Resch.*, *13*, pp. 213-223. 1918.

moisture (150) in which the small micro-organism may find a more or less permanent refuge. Apparently the microbiological population of dry soils[2] retain their physiological functions for much greater periods than seeds retain their germination powers. While slow drying tends to conserve the microbiological population of the soil mass, alternate wetting and drying may cause a comparatively high death rate of the vegetative cells. This fact may be one of the contributing factors to the low biological content of the surface soil.

Water also plays a very important part in the metabolic function by acting as a carrier and absorbent of the products formed. It is well known that life processes are influenced by the proximity of decomposition products. Therefore the oxidized and reduced products, also the waste products of metabolism, would tend to destroy or seriously limit the activity of the organism if not removed. The major portion of these products, gaseous, liquid, and solid, are soluble in water, some directly, others influenced by the solubility of something else. The water acts as a removing agency, sometimes as a direct carrier, more often as a medium through which the solutes may diffuse and be subject to further biological, chemical, and physical change.

303. Temperature.—Thermal phenomena affect life processes both physically and chemically. Physically they influence the viscosity of the liquids composing the cell, chemically they regulate the reacting velocities taking place. All life is governed by the limits of its temperature relations.

The vegetative cells of micro-organisms consist of comparatively small amounts of protein material and a large amount of water. The former coagulates at 70 to 80° C., the latter freezes at approximately 0° C. Roughly these temperatures are the limits of microbiological functions. There are, however, a maximum and minimum thermal point, above or below which a specific organism will not develop. Somewhere between these two extremes there is an optimum thermal point, at which, if

[2] Giltner, W., and Langworth, H. V., "Some Factors Influencing the Longevity of Soil Micro-Organisms Subject to Desiccation with Special Reference to the Soil Solution," *Jour. Agric. Resch.*, *5*, pp. 927-942 (1916) found that micro-organisms resisted drying longer in a clayey than in a sandy soil; while Lipman, C. B., and Burgess, P. S., in "Studies on Nitrogen Fixation and Azobacter Forms in Soils of Foreign Countries," *Cent. f. Bakt.*, *11*, pp. 481-511 (1915) found active organisms in soils kept dry in stoppered museum bottles for periods ranging from five to twenty-five years.

other conditions are favorable, growth rate and metabolic functions are at the maximum.

The temperature requirements of various species of micro-organisms differ. This characteristic has enabled them (particularly the bacteria) to be grouped into three classes, whose temperature relationships are approximately as follows:

Name of Group	Functions Cease Minimum	Functions Greatest Optimum	Functions Cease Maximum
Psychrophilic	0°C.	15°C	30°C
Mesophilic	15	37	45
Thermophilic	40	55	70–80

The majority of the soil micro-organisms belong to the first two groups. It is quite possible that the mesophilic group predominates during the warmer and the psychrophilic during the cooler seasons.

While microbiological activities are at a maximum during the summer (at least in humid areas), this does not mean that they entirely cease during the winter. There is apparently some slow action taking place at low temperatures,[3] even in frozen soil. This indicates that low temperatures have a retarding, rather than an inhibiting, effect on the metabolic functions. A reduction of temperature even to that of liquid hydrogen (—252° C.) apparently does not seriously harm bacteria and fungi, provided the thermal changes are not too rapid. An increase of temperature, *i.e.* above the maximum, on the other hand, rapidly causes a cessation of activities, a reduction of virulence, and if continued for a long period or is rapidly increased or fluctuated, results in death.

From the temperature standpoint, the soil micro-organisms differ quite markedly from those concerned in the functioning of the human organism. The latter micro-organisms (parasitic or non-parasitic) have a comparatively narrow temperature range that limits their activities. The soil micro-organisms function under a temperature range that for short periods may not be proportionately wider, but from season to season may vary

[3] Conn, H. J., "Bacteria of Frozen Soils," *New York Agric. Expt. Sta.* (Geneva) *Tech. Bul.* 35. 1914.

Vass, A. F., "The Influence of Low Temperature on Soil Bacteria," *New York Agric. Expt. Sta. Cornell Memoir* 27. 1919.

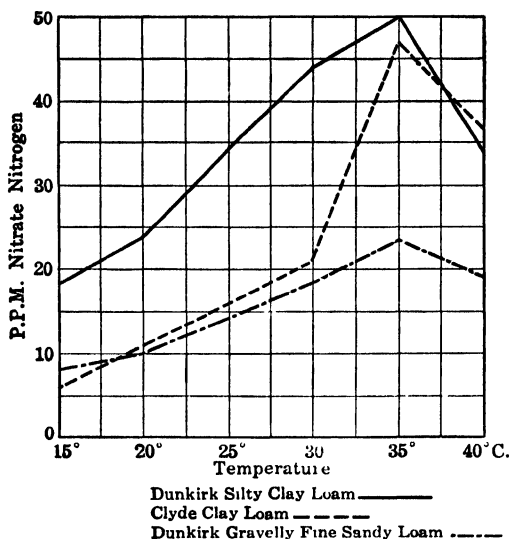



Fig. 26.—Effect of temperature on nitrification in soils.

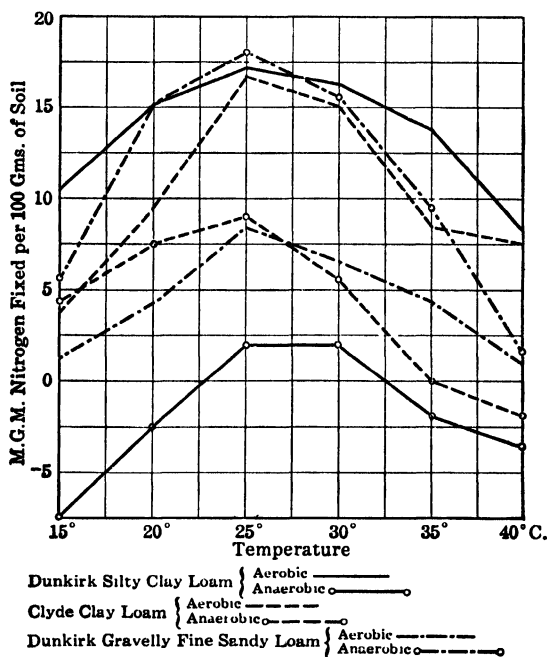



Fig. 27.—Effect of temperature on nitrogen fixation in soils.

considerably. Apparently many of the species have the ability to adapt themselves to this environmental change.

Panganiban [4] found a relationship existing between constant soil temperature and biological activities (see Figs. 26 and 27). The relationship varied in the three types of soil used. If, however, the temperatures were varied the results varied, particularly with nitrification. For instance, alternating the tempera-

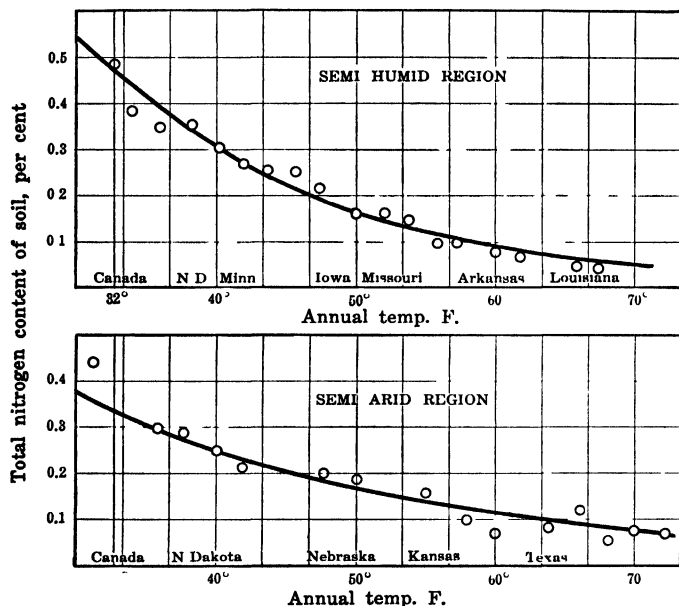



FIG. 28—Relationship of soil nitrogen and soil temperature.

tures depressed the process very greatly. With a ten-day change the incubation starting at higher and ending at lower temperatures showed a much lower nitrate formation than when incubated in the reverse order. Jenny [5] assumes the distribution of the soil's organic matter and consequently its nitrogen content to be related to climate, hence to temperature and humidity. A grouping and study of a large number of soil analyses show (Fig. 28)

[4] Panganiban, E. H., "Temperature as a Factor in Nitrogen Changes in the Soil," *Jour. Amer. Soc. Agron.*, *17*, pp. 1-31. 1925.

[5] Jenny, H., "The Relation of Climatic Factors to the Amount of Nitrogen in Soils." *Amer. Soil Survey Asso. Rept. Bul. 9*, pp. 163-173B. 1928. Also *Jour. Amer. Soc. Agron.*, *20*, pp. 900-912. 1928.

that the nitrogen content of the soils of the United States and Canada decreases from north to south and that this decrease bears a marked relationship to temperature.

304. Light.—Light affects the activities of soil micro-organisms in various ways. Direct sunlight is highly injurious to most forms, many being almost instantly killed when exposed to the full action of the sun's rays. Diffused daylight has an inhibiting effect on bacterial activity. The different colors of the spectrum do not act alike. The longer rays, from red to green, have little influence, while the shorter rays, blue and violet, may be deadly. Bacterial activity therefore is in general most pronounced in the absence of light.

On the other hand, the growth of algae is stimulated by the presence of diffused light, as also is the production of pigments by certain bacteria and the production of chlorophyll by certain protozoa. Apparently diffused light has little effect on the growth of fungi, both fleshy and filamentous. Direct sunlight, however, appears to be detrimental. For instance, the growth of algae takes place in shaded positions, north slopes, north sides of trees, etc.

There is no question regarding the importance of light in the growth and functions of the higher plants. In this respect light becomes an indirect factor in the control of the organic-matter content of the soil mass. The small amount of organic matter produced by algae and other forms is insignificant in comparison with that produced by higher plants. Further, the upper portion of the soil contains rather a meager population, especially if the soil is exposed to direct sunlight. The reason, however, may be attributed more to variations in moisture than to the influence of light.

305. Air.—In discussing the relationships of the soil air to the functions of micro-organisms, it must be kept in mind that the air content (gaseous phase) of the soil mass is entirely different from that of the atmosphere **(112)**. Further, the composition of the soil air is constantly undergoing change, and the gaseous composition of any one horizon or sub-horizon may not bear any specific relation to that of any other horizon. In fact, little is known of the gaseous complexes occurring in the soil. We do know, however, that the functions of micro-organisms are governed by their relations to their gaseous environment, in particular, oxygen.

All organisms need oxygen in their metabolic processes. The higher organisms (plants and animals) can only secure their oxygen from the gases of the atmosphere. They cannot live in an atmosphere devoid of this element. The micro-organisms are decidedly more elastic in their oxygen relationships. They may secure their oxygen from the atmosphere or in some cases from their food. The oxygen secured from food (292) is usually taken from the organic combinations, carbohydrates, proteins, etc., but may be taken from such inorganic combinations as nitrates, sulfates, etc.

Oxygen is utilized by micro-organisms to oxidize carbon in the securing of energy (259, 283). Under ordinary field conditions the greater part of the carbon added by the remains of higher plants is decomposed. In other words, the carbon compounds are changed from the solid to the gaseous form. Naturally this process markedly affects the composition of the soil air. The amount of carbon dioxide produced is frequently taken as a measure of biological activities. As these activities are governed by the several factors being discussed in this chapter, it may be assumed that carbon dioxide production, under field conditions, is more or less variable and that the carbon dioxide content of field soils varies considerably. If, however, the conditions are controlled, the production of carbon dioxide closely follows the increase or decrease in numbers of the soil population and in the metabolic functions of the organisms. For instance, the addition of easily decomposable organic matter is usually attended by an increase in numbers and an increase in carbon dioxide production. As the soluble carbohydrates are utilized and food assimilation becomes more difficult, the rapid increase in numbers first noted gives way to a stability of numbers, also to a rather constant rate of carbon dioxide production. As the process nears completion, the number of organisms decreases, with a corresponding decrease in gas production.

It must not be assumed that all micro-organisms are utilizers of oxygen. Some of them (a few protozoa, some bacteria, and the algae) are able to assimilate inorganic materials the same as the higher plants. In this case the carbon dioxide is synthesized to organic compounds and the oxygen is, in the main, set free,

In some cases light is required for the process, in others, *i.e.* the algae, the process is apparently capable of accomplishment

in the lowest soil depths in which micro-organisms are found. It appears that many of the higher plants growing under conditions of a limited oxygen supply are dependent upon the presence of algae to furnish this element. Rice[6] appears to be the outstanding economic plant requiring this relationship.

While the air content of the soil mass is markedly affected by its microbiological population, usually their functions influence mainly the carbon dioxide and oxygen relationships. If, however, the soil population is shifted from an aerobic to an anaerobic condition, or is supplied with large amounts of organic matter primarily of animal origin, the metabolic functions of the organisms will necessarily change and the air content will be influenced accordingly. Under anaerobic conditions unoxidized or reduced products will result and the carbon will more slowly decompose, the gaseous portion being in the form of methane, carbon monoxide, and carbon dioxide, etc. The nitrogen content of the protein may be denitrified (297), while the sulfur will be converted mainly to hydrogen sulfide.

306. Reaction.—The reaction (acid, neutral or alkaline condition) of the soil mass has a definite influence on its biological functions. An acid soil favors the development of fungi, but is usually unfavorable to the development of other forms. Usually the beneficial micro-organisms develop best in an approximately neutral medium. A slight variation either side of the neutral point may, like the higher plants (262), be allowed, the variation to the acid side being greater than to the alkaline. In general the actinomycetes prefer a reaction of 7.0 to 7.5, the

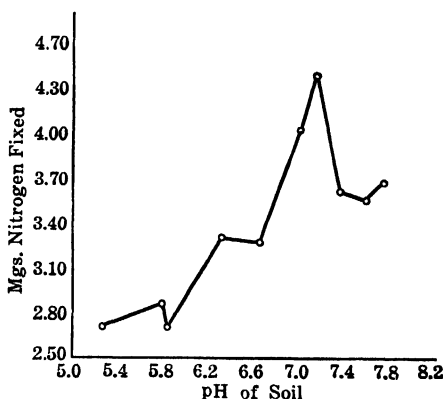



FIG 29—Influence of soil reaction on nitrogen fixation.

[6] Clements, F. E., "Aëration and Air Content, the Rôle of Oxygen in Root Activity," *Carnegie Inst. Washington. Pub. No. 315.* 1921.
Weaver, J. E., *Root Development of Field Crops.* McGraw-Hill Book Co. New York, 1926. 291 pp.

bacteria 6.0 to 7.0, and the fungi, 4.0 to 4.5. The protozoa prefer the same reactions as the bacteria. Thus it becomes evident that the reaction range for the majority of the soil population is essentially the same as for higher plants (see Table 47). Krishna[7] shows that there is a progressive increase in nitrogen fixation with decreasing acidity (Fig. 29). This correlation persists apparently irrespective of the treatments accorded or of the crops grown on the soil.

307. Food Supply.—While micro-organisms require the same plant-food elements as higher plants, they vary greatly in the manner in which they may utilize them. Some are independent of organic plant materials, others wholly dependent, some require the presence of nitrogen in their organic food materials, others are less dependent. The micro-organisms concerned in biological soil processes may be divided, according to their food requirements, into three groups as follows:

I. Autotrophic Micro-organisms.—Organisms that, like the higher plants, can form both carbohydrates and protein from carbon dioxide and inorganic salts. The autotrophic bacteria, the algae, etc., belong to this group.

These organisms are (from the standpoint of their relations to the production of food for higher plants) possibly the most important group of soil micro-organisms. They are active oxidizers, securing their energy by the oxidation of inorganic elements or compounds of nitrogen, sulfur, carbon, iron, and other materials. The organisms concerned in the oxidation of nitrogen (296) and in the oxidation of sulfur and its compounds are probably the most important of the group. The two processes are somewhat different, as nitrogen oxidation is usually inhibited by the presence of organic matter, while sulfur oxidation is apparently benefited or in some cases is not influenced. Also the first process has a rather narrow reaction range, pH 6.5 to 7.9, while the latter has a very wide range, pH 0.5 to 9.0.

II. Nitrogen-fixing Micro-organisms.—Organisms that need organic carbonaceous compounds, but do not require organic nitrogen. These forms are able to synthesize protein substances by using carbon as energy. The nitrogen may be taken from the atmosphere or from such inorganic forms as ammonia, nitrites,

[7] Krishna, P. G., "Soil Reaction and Nitrogen Fixation," *Jour. Amer. Soc. Agron.*, *20*, pp. 515-518. 1928.

or nitrates. This group is represented by the nitrogen-fixing forms in the soil. The members of this group are confined almost entirely to the bacteria.

III. Heterotrophic Micro-organisms.—Organisms that, like the higher animals, require both organic carbon and nitrogen compounds. These organisms cannot synthesize either carbon or nitrogen from inorganic sources. The "heterotrophic" group of micro-organisms. The group comprises that great group of soil life (the majority of the bacteria, the fungi, both fleshy and filamentous, the protozoa, etc.) that are concerned mainly with the various steps in the complicated system of decomposition. Their action is always destructive, always tending to reduce the compounds attacked to simpler and simpler combinations. While their products may be beneficial to plant growth, the organisms themselves are in reality competitors of the plants for food materials.

308. Relations of Microbiological Functions to the Plant Food Elements.—It becomes evident that in the destructive decomposition of organic matter and in the constructive building up of the cell of the micro-organism, there are numerous reactions involving the solubility of the soil constituents used by plants as food (292). Before considering these reactions certain facts must be remembered, viz.:

Plants consist of a number of elements. Usually C, H, O, P, K, N, S, Ca, Fe, and Mg are considered as the most important.

Both the air- and the soil-derived elements are added to the soil mass as organic matter.

In the decomposition of organic matter, five elements or their combinations (oxygen, hydrogen, carbon, nitrogen, and sulfur) may assume the gaseous state. The other elements listed above never assume a gaseous state.

The elements capable of forming gases are acidic in nature, hence form mainly acid radicles; the others, excepting phosphorus, are basic. The various acids usually combine with the bases.

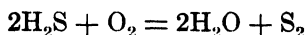
Assuming that the elements carbon, nitrogen, and sulfur represent the gaseous elements and that phosphorus, calcium, and potassium (or any other metallic ion) represent the basic, we may summarize the influence of microbiologic activities as affecting the soil-derived plant food as follows, illustrating the actions

on the element itself and the related activities on the basic materials:

SULFUR

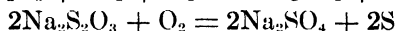
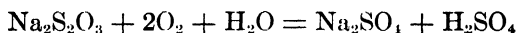
I. Direct Effects.—Biological changes involving sulfur transformations usually and markedly increasing the acidity.

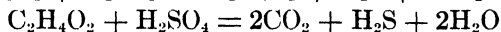
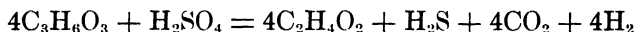
The sulfur of hydrogen sulfide may be changed from the gaseous to the solid state:

$$2H_2S + O_2 = 2H_2O + S_2$$

Elemental sulfur may be oxidized to a strong acid:

$$2S + 3O_2 + 2H_2O = 2H_2SO_4$$

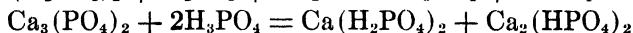
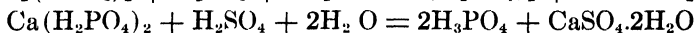
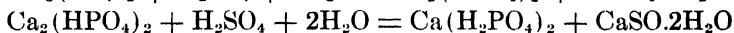
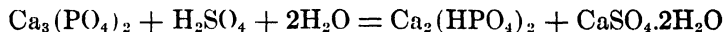
Thiosulfates may be oxidized to sulfates:

$$Na_2S_2O_3 + 2O_2 + H_2O = Na_2SO_4 + H_2SO_4$$
$$2Na_2S_2O_3 + O_2 = 2Na_2SO_4 + 2S$$

The sulfates may be reduced in the presence of organic matter:

$$4C_3H_6O_3 + H_2SO_4 = 4C_2H_4O_2 + H_2S + 4CO_2 + 4H_2$$
$$C_2H_4O_2 + H_2SO_4 = 2CO_2 + H_2S + 2H_2O$$

II. Indirect Effects.—The strong acid reacts readily with all bases:

$$CaCO_3 + H_2SO_4 = CaSO_4 + H_2O + CO_2$$

In the presence of tri-calcium phosphate, sulfuric acid gives, first, dicalcic phosphates, second, monocalcic phosphates, and finally phosphoric acid.

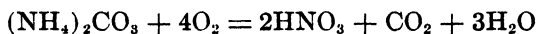
$$Ca_3(PO_4)_2 + H_2SO_4 + 2H_2O = Ca_2(HPO_4)_2 + CaSO_4.2H_2O$$
$$Ca_2(HPO_4)_2 + H_2SO_4 + 2H_2O = Ca(H_2PO_4)_2 + CaSO.2H_2O$$
$$Ca(H_2PO_4)_2 + H_2SO_4 + 2H_2O = 2H_3PO_4 + CaSO_4.2H_2O$$
$$Ca_3(PO_4)_2 + 2H_3PO_4 = Ca(H_2PO_4)_2 + Ca_2(HPO_4)_2$$

NITROGEN

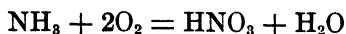
I. Direct Effects.—The protein compounds decompose with the formation of ammonia **(295)**. The ammonia may form combinations or be oxidized **(296)** to the acid state.

Urea is decomposed to ammonium carbonate:

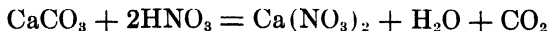
$$CO(NH_2)_2 + 2H_2O = (NH_4)_2CO_3$$

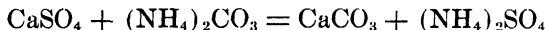
The ammonium carbonate may be nitrified, oxidized:

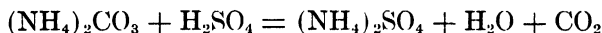
$$(NH_4)_2CO_3 + 4O_2 = 2HNO_3 + CO_2 + 3H_2O$$

Ammonia produced in ammonification may be oxidized:

$$NH_3 + 2O_2 = HNO_3 + H_2O$$

II. Indirect Effects.—The nitric acid reacts more or less readily with all bases, forming highly soluble salts.

In the presence of lime materials:

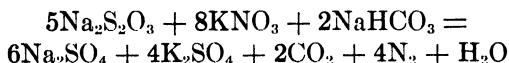
$$CaCO_3 + 2HNO_3 = Ca(NO_3)_2 + H_2O + CO_2$$

If sulfur compounds are present a double decomposition may take place, as in the use of gypsum in the preservation of manure:

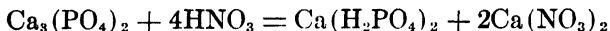
$$CaSO_4 + (NH_4)_2CO_3 = CaCO_3 + (NH_4)_2SO_4$$

or a direct combination will be made with the sulfuric acid:

$$(NH_4)_2CO_3 + H_2SO_4 = (NH_4)_2SO_4 + H_2O + CO_2$$

Under anaerobic conditions or conditions favorable for the reduction of nitrates, the denitrifying organism may oxidize sulfur or sulfur compounds at the expense of the nitrates as follows:

$$5S + 6KNO_3 + 2CaCO_3 = 3K_2SO_4 + 2CaSO_4 + 2CO_2 + 3N_2$$

or

$$5Na_2S_2O_3 + 8KNO_3 + 2NaHCO_3 = 6Na_2SO_4 + 4K_2SO_4 + 2CO_2 + 4N_2 + H_2O$$

It is possible that under some conditions phosphates may be attacked:

$$Ca_3(PO_4)_2 + 4HNO_3 = Ca(H_2PO_4)_2 + 2Ca(NO_3)_2$$

Carbon

The presence of some form of carbon is required for practically all biological reactions. If this element or its combinations were removed from the soil, all biological functions would either cease or be reduced to such a point as to be practically inactive. As carbon is the main source of energy **(283),** so is it the main source of soil activities, especially the chemical and biological.

I. Direct Effects.—Carbon compounds decompose to form various acids (Fig. 25) which in turn react with the mineral soil constituents. These compounds are further decomposed to give water, carbon dioxide, and the carbonate of the mineral combination. The water and carbon dioxide form the carbonic acid (H_2CO_3) of the soil solution. This acid is undoubtedly the most important in all soil processes. Its importance is not due so

much to its strength as a solvent as it is to the large amount and wide distribution in nature.

The solubility of various compounds is increased by carbonic acid:

$$CaCO_3 + H_2CO_3 = Ca(HCO_3)_2$$

$$Ca_3(PO_4)_2 + H_2CO_3 = Ca_2(HPO_4)_2 + CaCO_3$$

$$Ca_3(PO_4)_2 + 4H_2CO_3 = Ca(H_2PO_4)_2 + 2Ca(HCO_3)_2$$

$$3KAlSi_3O_8 + H_2CO_3 = KH_2Al_3Si_3O_{12} + K_2CO_3 + 6SiO_2$$

Lime compounds may be formed as in the case of metamorphic rocks:

$$\underset{\text{Olivine}}{2Mg_2SiO_4} + 2H_2O + CO_2 = \underset{\text{Serpentine}}{Mg_3H_4Si_2O_9} + \underset{\text{Magnesite}}{MgCO_3}$$

or

$$\underset{\text{Diopside}}{3MgCaSi_2O_6} + 2H_2O + 3CO_2 = \underset{\text{Serpentine}}{Mg_3H_4Si_2O_9} + \underset{\text{Calcite}}{3CaCO_3} + \underset{\text{Quartz}}{4SiO_2}$$

II. Indirect Effects.—The indirect effects of carbon transformations on the different soil compounds are possibly legion. The concentration of the soil solution is possibly due more to this element and its compounds than to any other factor. As the main source of energy it is the center of activities about which practically all nitrogen fixation-processes take place. Not only does it play an important part on the acid side of soil reaction, but also plays an important rôle in alkaline soils; for instance, calcium bicarbonate and alkaline sulfates may doubly decompose:

$$Ca(HCO_3)_2 + Na_2SO_4 \rightleftarrows 2NaHCO_3 + CaSO_4$$

309. Food Utilization an Environmental Factor.—As the growth of higher plants is controlled mainly by the sum of optimum environmental factors, so are microbiological activities controlled in a similar manner. The sum of the factors affecting plant growth in the soil mass plus the presence of biological life and decomposable organic matter govern the kinds of microorganisms functioning and the various products formed. For instance, variations in temperature, water, reaction, etc., may, even in the presence of the complex soil population, cause variable results. If a certain environmental condition persists or predominates, this factor may not only govern the use of organic matter as food, but may even be a physical factor of major importance. The presence of water in large amounts implies anaerobic condi-

tions. The presence of large amounts of organic matter high in carbon, possibly low in nitrogen, implies a food material difficult of decomposition. In the case of peat areas these two conditions practically paralyze decomposition processes. This is due to the fact that the waters are usually quiescent, become saturated with the metabolic products which acting as toxins serve to limit biological processes.

310. Microbiological Relations.—In a medium as variable in composition as the soil mass and populated with such a heterogeneous collection of biological life, it is but natural that the different species would materially affect each other. There is apparently a never-ceasing competition between all forms for food. Some forms habitually live on other forms. There is also an apparent sequence of species; for instance, the decomposition of organic matter is accomplished step by step, certain groups being active at one stage of decomposition and practically inactive at others. In addition there is apparently throughout the whole system of biological soil functions a great many interdependent relationships that may approach the state of symbiosis. On the other hand there is also an existent state of antagonism between some forms, if not by direct contact then indirectly by such metabolic products as acids, gases, toxins, etc.

CHAPTER 24

BIOLOGICAL FUNCTIONS AND PLANT GROWTH

The growth of higher plants is absolutely dependent upon three factors: first, the characteristics of the individual; second, the environment, temperature, moisture, etc.; and third, the supply of plant-food nutrients, the mineral elements. If these three factors are in adjustment the individual will develop normally. This fact is proved by many varied experiments, primarily in sand or water cultures, showing the ease with which plants may be brought to maturity without contact with the soil. In other words, normal plant growth will take place independent of the soil. The soil therefore may be regarded merely as a source of supply for mineral elements and as a mechanical support for plants.

Nature, however, has designated the soil as the proper home for plants. She evidently abhors a bare spot and has endeavored to cover all areas with plant life. Further, she has populated the soil mass with a flora and fauna that is represented by numerous species. Every possible area is filled to capacity with these forms of biologic life that are more or less adapted to their environment. Each of the various forms has certain functions, the performance of which, or the results of which, may have a marked bearing on the function of some other form. As a result the growth of plants under normal conditions (assuming that the physical factors and the chemical factors are at an optimum) is closely connected with the biological functions. These connections are naturally reflected in the growth of plants.

311. Stimulative and Retardative Effect.—The intensely crowded conditions under which plants have survived and the keen competition for food among all forms have produced throughout the ages a great variation in plant habits. These variations are very marked in the case of the micro-organisms. Some—for instance, the algae—are independent of higher plants,

but the majority of micro-organisms either directly or indirectly bear a certain relationship. In some cases the relationship is quite close—the micro-organism may be either an obligative or facultative parasite or saprophyte. Higher plant life is continually waging a continuous warfare against parasitic invasion of their tissues. In many cases the action results unfavorably and plant growth is checked. In some cases the invading organism is not only checked but its functions are made use of by the plant—sometimes to a marked advantage—and plant growth is stimulated. For instance, certain bacteria are made use of in the production of nodules **(316)**, while certain fungi are made use of in the production of mycorrhizas.

Biological Functions Stimulating Plant Growth

The various biological soil functions stimulating or increasing plant growth may be considered as directly affecting the plant itself or causing some other effect which is later reflected in an increased growth. A few of these functions are concerned with higher plants; the majority, however, are confined to the microorganic population of the soil.

312. Functions Directly Affecting the Plant.—The biologic functions directly stimulating plant growth may be divided into three groups: First, those forms of plant life that use the plant as a host and live within the plant itself. Second, those forms of plant life that use the plant as a host but do not live entirely within the tissues. Third, those forms that are not directly connected with the plant. The first two groups are commonly called symbiotic because of their habit of living in a state of mutual help with the plant. The third group is usually called associative.

313. Symbiotic Micro-Organisms.—There are many illustrations of symbiosis in the plant and animal world. Apparently the host supplies certain materials for the use of the invader. The latter reciprocates by performing some function of value to the host. In the case of the soil micro-organisms the invader apparently secures from the host everything essential for its development except the element nitrogen. It secures this element from the atmosphere by the process of nitrogen-fixation **(298)**. The invading organism either fixes more nitrogen than it needs, or is unable to prevent the plant from assimilating a portion

of the amount fixed. In any event the plant benefits [1] in various degrees by the relationship.

314. Organisms Functioning Wholly within the Plant.—The family *Leguminosae* is characterized as one that is markedly stimulated by its symbiotic relationship with bacteria. The relation is so pronounced that in many cases the economic plants, alfalfa, clover, beans, peas, etc., may be profitably inoculated. The causative organism is referred to by different names,[2] the Committee on Terminology of the Society of American Bacteriologists recommending the name *Rhizobium leguminosarum*.

The organism attacks the roots primarily,[3] producing a swelling that is commonly spoken of as a nodule. The power of the organism to infect plants is apparently limited to the legume family, while certain strains of the organism seem to be limited to certain members of this family. That is, organisms isolated from the nodule of one kind of legume may or may not be able to produce nodules on the roots of other legumes,[4] or even the same species of legume. In fact, there are apparently many species of the legume family that do not produce nodules.

315. Grouping of Legumes Forming Nodules.—Many cross-inoculation experiments have resulted in the legumes commonly in use being divided into groups based on the ability of a certain strain to produce nodules within that group. Pieters [5] lists the many groups as follows:

[1] Whiting, A. L., "A Biochemical Study of the Nitrogen in Certain Legumes," *Ill. Agric. Expt. Sta. Bul. 179.* 1915.
Fred, E. B., Whiting, A. L., and Hastings, E. G., "Root Nodule Bacteria of Leguminosae," *Wis. Agric. Expt. Sta. Resch. Bul. 72.* 1926.

[2] This organism appears in the literature under many names. The following genera have been used: *Schinzia, Phytomyxa, Cladochitrium, Bacillus, Rhizobium, Bacterium, Micrococcus, Rhizobacterium, Pseudomonas,* etc., with a very large number of species. The most common names are *Bacillus radicicola, Bacterium radicicola,* and *Pseudomonas Radicicola.*

[3] Certain tropical plants are reported as having nodules on their leaves. See Faber, F. C. von, "Das Erbliche Zusammenleben von Bakterien und Tropischen Pflanzen," *Jahrb. wiss. Bot., 51,* pp. 285-375. 1912.

[4] Burrill, T. J., and Hansen, R., "Is Symbiosis Possible between Legume Bacteria and Non-Legume Plants?" *Ill. Agric. Expt. Sta. Bul. 202.* 1917. Bibliography practically complete to 1915.
Helz, G. E., Baldwin, I. L., and Fred, E. B., "Strain Variation and Host Specificity of the Root Nodule Bacteria of the Pea Group," *Jour. Agric. Resch., 35,* pp. 1039-1055. 1927.
Leonard, L. T., "Lack of Nodule Formation in a Sub-Family of the Leguminosae," *Soil Science, 20,* pp. 165-167. 1925.

[5] Pieters, A. J., *Green Manuring, Principles and Practice,* p. 140. John Wiley & Sons, Inc. New York, 1927. 356 pp.
See also Löhnis, F., and Leonard, L. T., "Inoculation of Legumes and

I. Alfalfa Group.—Alfalfa, sweet clover, bur clover, fenugreek, and yellow trefoil.

II. Red Clover Group.—Berseem and the following clovers: alsike, crimson, hop, rabbit's foot, red, mammoth red, shaftal, white, zigzag, least hop, buffalo, cariolina, small-flowered, strawberry, and hungarian.

III. Cowpea Group.—Cowpea, peanut, acacia, tick trefoil, partridge and pigeon peas, kudzu, dyers greenwood, furze, silky lespedeza, japan clover; and the following beans: rice, jack, adzuki, asparagus, juga, lima, hyacinth, moth, mung, sword, tepary, and velvet.

IV. Vetch Group.—The following vetches, woolly pod, hairy, narrow leaf, purple and common, also the horse bean, lentil and the following peas, canada field, garden, perennial sweet, sweet, tangier, and veiny.

V. Soy Bean Group.—Soy bean.

VI. Bean Group.—The garden, pinto, and scarlet runner bean.

VII. Lupine Group.—The blue, yellow, white, and wild lupine, also serradella.

316. Nodules.—Little is known of the means whereby the organism secures entrance into the root. Infection apparently takes place through the root hairs. The plant, however, succeeds in localizing the zone of infection by confining the activities of the invading organisms to the parenchymatous tissues. As a result the nodule is more or less weakly attached to the main root and does not change its direction of growth. The latter is an important characteristic, distinguishing the true nodule from the nodule-like swelling produced by nematode **(323)** infection.

Nodules are extremely variable in size and shape. Those produced on plants listed in groups III, V, and VI above are inclined to be spherical, usually of the size of small peas, and partially encasing the root to which they are attached. Those produced on plants listed in group II are small, pear-shaped, weakly attached at the small end, and more or less profusely scattered along the roots. Those produced on plants listed in groups I, IV, and VII are usually weakly attached as in group II, but are much larger and decidedly fingered. The fingering habit tends to produce blunt projections extending in all directions,

Non-Legumes with Nitrogen-Fixing and Other Bacteria." *U. S. Dept. of Agric. Farmers Bul. 1496.* 1926.

often forming characteristic balls, which in the case of the velvet bean may approximate the size of a golf ball.

317. Organisms Living Partially within or on the Exterior of the Plant.—A relationship claimed to be symbiotic has been found on the roots of many of the higher plants, particularly the ceanothus, alnus, elaeagnus, etc. This relationship, about which information is lacking, is possibly connected with nitrogen fixation apparently brought about by certain forms of fungi. The fungus may be filamentous or it may be fleshy. It usually produces local swellings spoken of as mycorrhizas.

318. Mycorrhizas.—Mycorrhizas are divided into two forms, according to the mode of attack and position of the growth on the host tissues. They are: (1) *ectotrophic,* when the shallower layers of the host are penetrated and a fungous sheath is formed about the parts attacked; (2) *endotrophic,* when the fungus penetrates deeply into the tissues of the host.

319. Factors Affecting Symbiosis.—Sybiotic relationship is merely reciprocal parasitism. In case one or the other of the individuals concerned gains the ascendency, the weaker becomes either the prey of the stronger or is repulsed in its attack. Further, there is strong reason to suspect that the invading organism is at first parasitic, and if the plant attacked is possessed of sufficient vitality, is unable to gain a foothold. This is shown by the fact that if plants capable of living in symbiosis with micro-organisms are supplied with a sufficient amount of available nitrogen, neither nodules or mycorrhizas are formed. There are also indications that the various physical and chemical factors affecting plant growth also affect the production of nodules. Apparently nodulation is at a maximum when the conditions for the growth of higher plants are at the optimum. As a result there are many cases [6] where nodulation has been retarded or stimulated by the presence or absence of various inorganic salts, lime, phosphates, sulfur compounds, etc., or by organic materials, the one outstanding exception being that the presence of soluble nitrogen in a form and amount to be of greatest advantage to the plant is decidedly a detrimental factor in nodule production and consequently in symbiotic nitrogen fixation.

[6] This subject has been reviewed in detail by Göbel, G., "The Relation of Soil Nitrogen to Nodule Development and Fixation of Nitrogen by Certain Legumes," *New Jersey Agric. Expt. Sta. Bul. 436.* 1926.

320. Stimulative Associative Effects.—There are many instances of associative effects in nature which are directly stimulative to plant growth. It is suggested that the rice plant is dependent upon the large supply of oxygen produced by the action of algae inhabiting the swampy soils in which this plant is grown. It has long been known that non-leguminous plants are benefited by the proximity of inoculated legumes. Lipman[7] placed an unglazed pot inside a larger glazed pot and filled both with soil. A non-legume was grown in the unglazed pot, an inocculated legume in the area surrounding it. The nitrogen supply was reduced to the minimum, yet the non-legume apparently benefited by the nitrogen that was able to diffuse through. Lyon and Bizzell present figures showing that the nitrogen content of non-leguminous plants grown in association with legumes is variable but may be markedly increased.

321. Biological Functions Stimulating the Plant Indirectly.—Many of the biological functions taking place in a normal soil have an indirect stimulative effect on plant growth. The various changes taking place in the decomposition of organic matter tending to liberate carbon dioxide, which in turn increases the solubility of insoluble compounds, are important. Higher plants may also produce this same effect. Metzger[8] found a higher concentration of bicarbonates in a majority of soil samples taken close to or around the roots of corn, wheat, and kaffir than in samples taken a short distance away. The maximum difference in concentration occurred at the fruiting period of the plants. Russell[9] states that the chief work of earthworms is to act as cultivators of the soil. They have little if any effect on the decomposition of organic matter and the nitrogen changes within the soil, but stimulate plant growth by their loosening, mulching, aërating action, and by the drainage action of their burrows. Hisaw[10] shows that the mole does perhaps more good than harm in uncultivated areas by destroying quantities of injurious

[7] Lipman, J. G., "The Associative Growth of Legumes and Non-Legumes," *N. J. Agric. Expt. Sta. Bul. 253.* 1912.

Lyon, T. L., and Bizzell, J. A., "A Heretofore Unnoted Benefit from the Growth of Legumes," *N. Y. (Cornell) Agric. Expt. Sta. Bul. 294.* 1911.

[8] Metzger, W. H., "The Effect of Growing Plants on Solubility of Soil Nutrients," *Soil Science, 25,* pp. 273-280. 1928.

[9] Russell, E. J., "The Effect of Earthworms on Soil Productiveness," *Jour. Agric. Sci., 3,* pp. 246-257. 1908-09.

[10] Hisaw, F. L., "Feeding Habits of Moles," *Jour. Mammalogy, 4,* pp. 9-20. 1923.

insects. The average daily consumption of food is 32 per cent of the body weight of the animal. The food is apparently preferred in the following descending order: earthworms, white grubs, larva of other insects, adult insects, corn, ripe tomatoes, vegetables, and fruits. In addition, the carbonaceous material of the soil mass serves as a source of energy for the non-symbiotic organisms and results in stimulating the fixation of nitrogen (298). It thus becomes evident that a preceding crop may become an indirect stimulator of the crop that follows. Lyon shows the effect of the preceding crop on the crops that follow in Table 48.

TABLE 48

YIELD OF CEREAL CROPS FOLLOWING EACH LEGUME OR MIXTURE OF LEGUME AND CEREAL[11]

(Yields in Pounds of Grain and Straw Combined, per Acre)

CROP PRECEDING THE CEREAL	1922 BARLEY	1923 RYE	1924 RYE
Red clover	3,331	5,585	6,970
Alsike clover	3,425	6,034	6,705
Alfalfa	3,877	6,180	7,445
Sweet clover	4,063	5,901	7,184
Wheat and vetch	2,422	3,210	4,850
Red and alsike clover	3,814	5,720	6,886
Sweet clover and vetch	4,220	6,128	6,836
Soy beans	1,473	3,460	3,939
Oats and peas	1,181	3,314	3,865
Field beans	1,212	3,068	4,221
Oats or rye	1,155	2,147	2,055

The soil in which the crops were grown was sandy and poor in nitrogen. The plots were alternated in order that the crops should be grown the year preceding the cereal. The soil was liberally supplied with lime, phosphoric acid, and potash in order that nitrogen should be the limiting factor.

BIOLOGICAL FUNCTIONS RETARDING PLANT GROWTH

Nature's law is apparently "the survival of the fittest." Under natural conditions thousands of plants may pass the seedling stage, but only a comparative few reach maturity. In the case of the economic plants, the crowded competitive natural conditions are relieved, yet there are biologic soil conditions that

[11] Lyon, T. L., "The Effect of Some Legumes on the Yield of Succeeding Crops," *N. Y.* (Cornell) *Agric. Expt. Sta. Bul.* 447. 1925.

retard their growth. These conditions operate both directly and indirectly.

322. Retardative Effects Directly Affecting the Plant.—The retardative biologic soil functions directly affecting plant growth are essentially connected with the disease factor. The major portion of the total microscopic population of the soil is mainly obligative saprophytic or parasitic, a much smaller portion is facultative saprophytic or parasitic, while a few forms are obligate parasites. The obligate saprophytes do not affect plant growth directly. The parasitic micro-organisms, however, may become a serious factor in retarding plant growth. Jones *et al.*[12] state: "The associated abnormal host conditions which we term 'disease' are the resultants of the interaction of a plastic host and a plastic parasite under the play of variable environment." The work of these investigators indicates that the ability of a soil-borne micro-organism to infect a plant, and thus cause a diseased condition, is in many cases a function of the temperature relationship. "In all the cases studied (*e.g.* cabbage yellows, flax wilt, and tomato wilt) the evidence is similar. Invasion proceeds from the soil through the roots and advances through the vascular elements to the aërial parts. At all stages progress is conditioned upon favorable temperature relations. The general curve of disease development rises rather gradually to its optimum, which for all alike is about 28° C., then makes a sharp drop as temperature rises above this. In all cases there is an upper as well as a lower point beyond which the host may survive, in even the worst infected soil, free from evidence of the disease. In other words, in each case the host has a wider growth-temperature range than has the potential parasite." The temperature relationships of onion smut, *Urocystis cepulae,* was found to be quite different in that the disease is severe at low temperatures and disappears at about 28° C.

Johnson and Hartman[13] found that tobacco root-rot is favored by lower soil temperatures, the most favorable range being between 17° and 23° C. Webb[14] found that the mosaic disease of

[12] Jones, L. R., Johnson, J., and Dickinson, J. G., "Wisconsin Studies upon the Relation of Soil Temperature to Plant Disease," *Wis. Agric. Expt. Sta. Resch. Bul. 71.* 1926.

[13] Johnson, J.. and Hartman, R. E., "Influence of Soil Environment on the Root-Rot of Tobacco," *Jour. Agric. Resch., 17,* pp. 41-86. 1919.

[14] Webb, R. W., "Soil Factors Influencing the Development of the Mosaic Disease in Winter Wheat," *Jour. Agric. Resch., 35,* pp. 587-614. 1927.

wheat developed only within a relatively restricted soil temperature range. In the four temperatures of the experiment the disease appeared at 10° and 16° but not at 23° and 30° C. A high soil moisture-content favored both rosette and leaf mottling, while a medium moisture-content was less favorable.

What has been indicated for soil temperature holds in some degree for other variable factors, especially moisture, in limiting the activities of soil parasites. McKinney and Davis [15] found that a sudden reduction of the moisture supply increased infection in the case of foot-rot of wheat. Harter and Whitney [16] found that an increase of moisture increased the infection of sweet potatoes by the black-rot fungus. Kirby [17] found that the moisture, temperature, and reaction factors were all of importance in the take-all disease of cereals and grasses. A high moisture, high fall temperatures, and alkaline reaction were factors tending to cause increased infection. Potato scab,[18] caused by *Actinomyces scabies*, is comparatively more prevalent in regions having high summer temperatures than in those of lower temperature. The optimum soil temperature for potato scab appears to be about 23° C.

Various other soil conditions may become factors in causing plant disease. Valleau *et al.*[19] found that corn root-rot was enabled to cause a greater infection in sand than in soil. When the corn was grown in mixtures of sand and soil the injury was found to be in direct proportion to the amount of sand present.

Many illustrations, including temperature, moisture, climatic factors, nutritional conditions, etc., may be drawn showing the relationship of the soil plant-disease factor. In many cases the condition favoring the attack of the causative organism will exist for only a limited time. If, however, the invading organism once gains entrance into the host it usually persists. A diseased con-

[15] McKinney, H. H., and Davis, R. J., "Influence of Soil Temperature and Moisture on Infection of Young Wheat Plants by Ophiobolus Graminis," *Jour. Agric. Resch.*, *31*, pp. 827-840. 1925.

[16] Harter, L. L., and Whitney, W. A., "Influence of Soil Temperature and Moisture on the Infection of Sweet Potatoes by the Black-Rot Fungus," *Jour. Agric. Resch.*, *32*, pp. 1153-1160. 1926.

[17] Kirby, R. S., "The Take-All Disease of Cereals and Grasses Caused by *Ophiobolus cariceti* (Berkeley and Broome) *Saccardo*," *N. Y.* (Cornell) *Agric. Expt. Sta. Memoir 88.* 1925.

[18] Jones, L. R., McKinney, H. H., and Fellows, H., "The Influence of Soil Temperature on Potato Scab." *Wis. Agric. Expt. Sta. Resch. Bul. 53.* 1922.

[19] Valleau, P., Karraker, P. E., and Johnson, E. M., "Corn Root-Rot—a Soil-borne Disease," *Jour. Agric. Resch.*, *33*, pp. 453-476. 1926.

dition of the higher plants reflects itself in the soil functions. The organism itself may become saprophytic as in the case of the organism causing rhizoctonia,[20] or may lie in a dormant state. In any event there is a marked decrease in the amount of organic matter added to the soil mass, hence a decreasing supply of nitrogen and carbon and a limitation of the life-giving properties of the soil.

323. Nemas.—One of the most subtle soil-borne diseases retarding the growth of plants is caused by certain small worms spoken of as nemas or nematodes. These worms usually produce abnormalities or swellings on the roots, but may attack other portions of the plant. The characteristic root malformations have led to the practice of referring to the disease as root-knot, root-gall, or big-root. These worms occur as soil-borne pests in all except the most northern states and are prevalent in greenhouses.

The most widely spread and best known form of nematode is *Heterodera radicicola*. This animal in the earlier stages of its development is worm-like and for this reason has been called an eelworm. It hatches from an egg which is usually less than 1/250 of an inch long and appears as a worm 1/80 to 1/50 of an inch long and with a diameter about 1/30 of the length. The worms move with considerable activity through the soil by a thrashing, whip-like movement. When they find the root of a susceptible plant, preferably a young feeding root, they bore their way into it. The entrance is easily accomplished by means of a strong spearlike organ in the mouth. Once inside, active movement ceases, nourishment is absorbed from the root, and the organism begins to enlarge. The tissues of the root are irritated and also enlarge, forming swellings that may easily be mistaken by the uninitiated for nodules (316). The female increases rapidly in size, becoming pear-shaped and literally filled with eggs. A female is capable of producing upwards of 500 eggs. About four weeks are required for full development. The males are rarely seen except at certain periods. They also bore into the root, enlarge, shed their skins, and then bore out into the soil again.

324. Economic Importance of Nematodes.—Careful estimates made on the basis of actual surveys through typical agricultural counties in the southeast have shown the direct losses

[20] Dana, B. F., "The Rhizoctonia Disease of Potatoes." *Wash. Agric. Expt. Sta. Bul. 191.* 1925.

by nematode infection, due to reduced yields, to be enormous.[21] In some cases the losses were as much as 80 per cent. The loss for cotton in all sandy lands in a single county in South Carolina was estimated as 4.4 per cent, in Georgia as 4.1 per cent. In Florida the losses in the case of truck crops were estimated as follows: snap beans, 1.0 per cent, cabbage 20 per cent, celery 14 per cent, egg plant 21 per cent, potatoes 12 per cent, lettuce 8 per cent, peas 25 per cent, and tomatoes 13 per cent. In certain fields in Virginia (1918) the yield of wheat was decreased 40 per cent. In the latter case the attack was confined to the wheat-head. The losses in the case of sugar beets are variable but prevalent in all areas where the crop is grown.

325. Plants Attacked by Nematodes.—A large number of the commonly cultivated plants and many of the common weeds are attacked by nematodes, many of them severely. The following is a list of the more common plants subject to, or immune to, attack by *Heterodera radicicola*.

PLANTS SUBJECT TO ROOT-KNOT (GODFREY)

Field Crops	*Ornamental Plants*	*Truck Crops*	*Woody Plants*
Alfalfa	Begonia	Asparagus	Almond
Clover	Cineraria	Bean	Catalpa
Cotton	Clematis	Beet	Cherry
Cowpea (except Iron, Brabham, Monetta, and Victor)	Coleus	Cantaloupe	European elm
Pumpkin	Dahlia	Carrot	Fig
Soy bean (except Laredo)	Hollyhock	Celery	Mulberry
Sugar beet	Ginseng	Cucumber	Old World grape
Sugar cane	Goldenseal	Egg plant	Peach
Sweet potato	Peony	Lettuce	Pecan
Tobacco	Rose	Okra	Persian walnut
Vetch	Sweet pea	Onion	Weeping willow
	Violet	Pea	
		Pepper	
		Potato	
		Salsify	
		Spinach	
		Strawberry	
		Tomato	
		Watermelon	

[21] Godfrey, G. H., "Root-Knot; Its Cause and Control," *U. S. Dept. Agric. Farmers Bul. 1345*. 1923.

Byers, L. P., "The Eelworm Disease of Wheat and Its Control," *U. S. Dept. of Agric. Farmers Bul. 1041*. 1919.

Thorne, G., "Control of Sugar Beet Nematode by Crop Rotation," *U. S. Dept. of Agric. Farmers Bul. 1514*. 1926.

PLANTS IMMUNE OR ONLY SLIGHTLY SUSCEPTIBLE TO ROOT-KNOT

Barley	Kafir	Red top
Beggar weed	Milo	Rye
Broom-corn millet	Natal grass	Sorghum
Corn	Peanut	Timothy
Grasses (nearly all)	Pearl millet	

326. Detecting the Presence of Nematodes.—There are many species of parasitic nemas, some of which are more or less specific for certain plants. The total number of plant hosts known to be susceptible to these forms exceeds 660. Usually the presence of the parasite may be detected by the swellings on the roots. The swelling is a thickening of the root itself, and if growth extends beyond the swelling the original direction of growth is changed. Later the root thickens, becomes fleshy, and the plant may form numerous fibrous roots. In the earlier stages of the attack the swelling may easily be mistaken for a nodule **(316)** except for the fact that it is never to the side of the root, and further, the pinkish color characteristic of young nodules is absent.

Steiner[22] states, "Plants with nemic infestation might sometimes (perhaps under certain climatic or growth conditions) show no symptoms, and in other cases symptoms regarded as typical for nemic diseases might exist and no nemas be found." Nematologists therefore are rather skeptical about the common assumption that the disease may be recognized with much accuracy, and consider an examination with the microscope as the only safe way to determine the presence of nemas.

327. Retardative Biological Effects Indirectly Affecting Plants.—Comparatively little is known of the biological soil relationships indirectly affecting plant growth. It is known that when large amounts of organic matter are added to the soil **(226)**, the following crop is usually retarded in growth. The common explanation is that the organism concerned in the

[22] Steiner, G., "*Tylenchus pratensis* and Various Other Nemas Attacking Plants," *Jour. Agric. Resch.*, *35*. pp. 961-981. 1927.

See also Leukel, R. W., "Investigations on the Nematode Disease of Cereals Caused by *Tylenchus tritici*," *Jour. Agric. Resch.*, *27*, pp. 925-95[illegible] 1924.

Thomas, E. E., "The Citrus Nematode, *Tylenchus semipenetrans*," *Cal. Agric. Expt. Sta. Tech. Paper 2.* 1923.

Godfrey, G. H., "The Stem Nematode *Tylenchus dipsaci* on Wild Hosts in the Northwest," *U. S. Dept. of Agric. Department Bul. 1229.* 1924.

decomposition process is in active competition with the higher plants for the soil nutrients, particularly nitrogen. The previous crop may or may not have a marked effect on the crop that follows (Table 48). The associative influence of two or more crops grown together may become mutually retardative. The injurious effects of sod in apple orchards [23] is well known. Apparently this effect is chiefly concerned with the depleted nitrogen supply of the soil, but may also be concerned with the moisture relationships, production of toxic materials, etc. The influence of the preceding crop on the moisture content of the soil is amply demonstrated in dry farming areas, where crops are grown every other year. The production of toxic materials has not been amply demonstrated. The toxic materials, assumed to be excreted from the roots of one plant, are said to be injurious in the case of certain other plants. Rosen [24] shows that in the case of the cotton-wilt fungus two substances poisonous to cotton may be produced. One is a volatile compound with an alkaline reaction, the other is an inorganic salt in the form of a nitrite.

The above few illustrations merely indicate the vast field of biological soil relationships that may be stimulative or retardative in the case of higher plant growth.

[23] Lyon, T. L., Heinicke, A. J., and Wilson, B. D., "The Relation of Soil Moisture and Nitrates to the Effect of Sod on Apple Trees," *N. Y.* (Cornell) *Agric. Expt. Sta. Memoir 63*. 1923.

[24] Rosen, H. R., "Effects to Determine the Means by Which the Cotton-Wilt Fungus *Fusarium vasinfectans* Induces Wilting," *Jour. Agric. Resch.*, *33*, pp. 1143-1162. 1926.

CHAPTER 25

SOIL CYCLES

The activities of nature are never in a continuous straight line. One action influences another, the second affects a third, and so on until a point is reached where a certain action influences or initiates the first. The course of life's processes moves in a more or less well-defined cycle. Life forms are ceaselessly varied, shifted, and interchanged. Nothing abides, nothing can escape the ever-moving cycle. Men, beasts, plants, trees, rise up, grow strong, then weaken, give way, and finally pass on into the multitude of things that have been, there to be mixed, changed, merged into something else, possibly something young and new and strong.

It appears that the course of natural events is also cyclic, especially as applied to the soil. In some cases the cycle is clearly defined, in other cases the different phases are ill defined or, due to the time involved, are incomplete. One fact stands out, however; namely, that no action or reaction is independent. No phase of a cycle nor a cycle itself is the result of a single and continuous process. Rather, all processes are connected, interdependent, and correlated to such a degree that each insensibly merges into the other. This condition of affairs makes it imperative that a visualization of the cycles of nature be on more than one plane. In other words, the cycles of nature are more on the spherical than on the cyclic order.

328. The Water Cycle.—Possibly one of the simplest and most easily understood natural phenomena is the water cycle. As shown in Table 49, there is a definite and continuous movement of water in nature. It falls on the surface of the soil as rain, a portion is lost by leaching and percolation, another portion by vaporization, but both portions ultimately and within a comparatively short time, are again returned to the surface of the soil.

329. The Salt Cycle.—As water passes through the various cyclic stages it markedly affects the soil. Falling as pure water,

TABLE 49

BALANCE SHEET

CIRCULATION OF WATER ON THE EARTH'S SURFACE[1]

	CUBIC MILES	DEPTH IN INCHES	PER CENT
A			
Entire earth surface (196,911,000 miles)			
Evaporation of entire earth surfaces	92,121	29.5	80
Evaporation from land surfaces	23,270	7.5	20
Precipitation of entire earth surface	115,391	37.0	100
B			
Oceans (141,312,600 square miles)			
Evaporation from oceans	92,121	41.3	100
Amount of ocean vapor carried to the land (net*)	5,997	2.8	7
	86,124	38.5	93
C			
Peripheral land area (44,015,400 sq. mi.)			
Ocean vapor (net)	5,997	8.7	29
Continental vapor from the peripheral land surface	20,871	29.9	100
Precipitation over land surface	26,868	38.6	129
D			
Closed interior basins with no drainage to the ocean (11,583,000 miles)			
Evaporation from closed basins	2,399	13.0	100
Precipitation over closed basins	2,399	13.0	100

* The difference between the amount of vapor that escapes from land to the ocean and from the ocean to land.

it adds a small amount of plant-food materials to the soil, but percolating through the mass it usually carries away in solution more than is added, especially under humid conditions. The materials carried in solution and suspension are concentrated in the various large bodies of water, from which they are deposited by various means in diverse places and in varying combinations. The mobility of the chlorides, particularly of sodium and potassium, have long been of interest to some geologists. Such salts are quickly removed by percolation, concentrated in sea water and under favorable conditions form the great salt deposits, or as windborne salts are blown on the surface of the land. Many

[1] From Zon, R., "Forests and Water in the Light of Scientific Investigation," *Senate Document No. 469*, 62d Congress, 2d Session, 1927. Appendix V of the Final Report of the National Waterways Commission.

of the salt deposits, particularly the potassic, are being worked as a source of plant food. The calcic salts, however, are possibly of greatest agricultural importance. Large amounts of these salts are removed annually from the soil, but unlike sodium and potassium do not tend to accumulate in the larger bodies of water; in fact, the concentration of lime salts in many drainage areas is considerably less than that of the streams flowing into them. The extensive marine fauna remove and deposit as shells, plates, skeletons, etc., the salts as fast as they are brought in. The accumulation of the remains of these animals tends to form the great limestone formations. When these are elevated above the surface of the water, they in turn are attacked by various physical, chemical, and biological forces, the lime removed, and the residues left as soil.

330. The Physical Cycle.—To the geologist, the soil is more or less a condition of rock metamorphosis. That is, it is merely a stage through which surface rocks pass in going from one rock mass to another. The soil mass occupies the opposite position of the physical cycle (Fig. 30) to the rock mass. The rock mass is

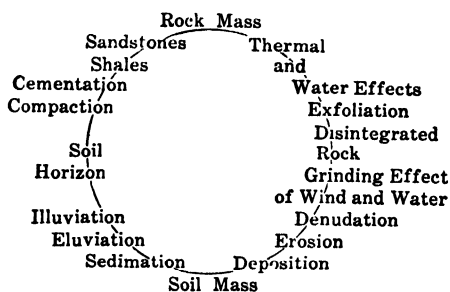



FIG. 30.—Physical soil cycle.

broken to smaller and smaller fragments by the various physical agencies. The fragments are usually moved in various degrees but deposited to form the soil mass. The sorting action of wind and water, of sedimentation, eluviation, and illuviation, favor the condition which, if undisturbed, gives rise to new rock forms. But the actual compaction and cementation of the mass is not strictly a physical phenomenon. The physical cycle is incomplete without the chemical and biological functions to effect cementation.

331. The Chemical Cycle.—The physical cycle of nature forms a working basis for the operation of the chemical cycle. While rock material may be reduced to the consistency of the soil mass by physical forces, the action in nature is comparatively

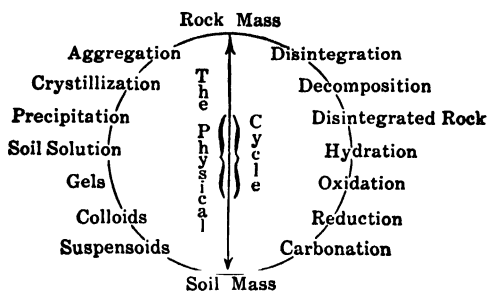



FIG. 31.—Chemical soil cycle.

slow. The entrance of water into the reaction not only stimulates the physical process, but introduces a multitude of chemical changes. The decomposition of limestones into soils is primarily a chemical and biological action, but the decomposition of the

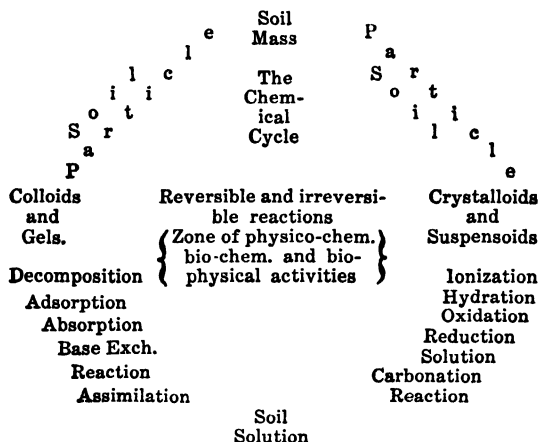



FIG. 32.—The physico-bio-chemical soil cycle.

majority of the soil-forming minerals is a combined effect of all forces. In the chemical cycle, the position of the rock and the soil mass is the same as in the physical cycle, but (Fig. 31) the intermediate changes are quite different.

The soil mass is the material governing the soil solution, but the concentration of the latter and its efficiency as a source of nutrients is dependent upon the functioning of the physico-chemical, bio-chemical, and bio-physical activities (Fig. 32).

332. Cycle of Elements Essential in Life Processes.—Many ingenious cycles have been proposed to illustrate graphically the chain of events through which the individual elements concerned in life's processes pass. The well-known nitrogen cycle[2] is familiar to all. Such cycles do not bring out the correlated activities and importance of all elements, but tend to emphasize the importance of one. It is important that, in a cycle of elements essential in life processes, all elements and all main stages be shown. Such a cycle may be constructed as follows:

333. The Arrangement of the Elements.—It is important that the essential elements be arranged in orderly fashion. Of the ten elements essential to life, five (oxygen, hydrogen, carbon, nitrogen, and sulfur) may occur free or may be in some combination in either the solid or gaseous condition. The five remaining elements (phosphorus, potassium, calcium, magnesium, and iron) never occur free, are never in the gaseous state (phosphorus may possibly occur as phosgene) and are always in combination. The importance of each of these groups may be considered in descending order of the above arrangement. A chain of the ten elements, descending in order of relative importance, may be constructed by placing oxygen and phosphorus on either side of the center of the chain.[3]

334. Phases Involved.—There are three well-defined phases in a cycle of elements concerned with life's processes; namely, (1) the constructive, (2) the stationary, and (3) the destructive, each of which are interdependent.

1. The constructive phase is that portion of the cycle in which the inorganic soil and air-derived elements or their combinations are converted by plant processes into complex organic compounds which may be used by the organism itself, by animals, or by other plants as food. This complex organic food furnishes the necessary energy for practically all life processes. In this phase

[2] *U. S. Dept. of Agric. Yearbook*, 1909, p. 202.

[3] In this discussion only the principals of a cycle are developed. It must be remembered that all life processes are not essentially the same, and that many processes, well defined in the case of higher plants, may be reversed in the case of the lower forms of life.

the inorganic food enters the body of the assimilating organism, usually in constantly increasing amounts thus increasing the size of the organism, but not necessarily increasing the complexity of the chemical combinations. This phase is characterized by continuing throughout the life of only the higher organisms.

2. The stationary phase is reached when the organism dies. It is the period between the death of the organism and the beginning of decomposition. Strictly speaking, organic matter in nature begins decomposing as soon as life functions cease, but there are many cases where the material may be naturally or artificially protected. When adequately preserved, the material will retain its structure for a long time.

3. The destructive phase is the reciprocal of the constructive, in which the complex chemical combinations are resolved into the simpler forms and thus may be rendered suitable for plant use. In other words, changed to a condition to again enter the cycle and pass through the chain of events.

335. The Cycle.—It is evident (Fig. 33) that the elements and combinations of elements on one side of the cycle agree with those on the other and that the plant, animal, and microscopic activities revolve in a number of planes. There is little evidence of an independent action, rather the activities are highly dependent upon each other. No indication can be given of the time involved. A micro-organism may pass through the cycle in a few hours; a plant, on the other hand, may take hundreds of years, or an element, combined and held in a rock mass, may not have completed the first stage.

336. The Action of Plant and Animal Life.—The activities of the higher life forms is confined to the constructive phase. It will be noted that at the beginning of life the organism is small but grows in importance and mass. The elements assimilated by the higher forms are, excepting oxygen, always in combination. The importance of animal life is less than, but dependent upon, plant life; hence plants when taken into the animal body are transferred to the destructive phase of the cycle where they are digested. The importance of micro-organisms in the constructive phase is slight. They do, however, play an important rôle in the assimilation of the elements nitrogen and sulfur.

337. The Action of Micro-organisms.—Micro-organisms are mainly the antithesis of plants One is constructive in its activi-

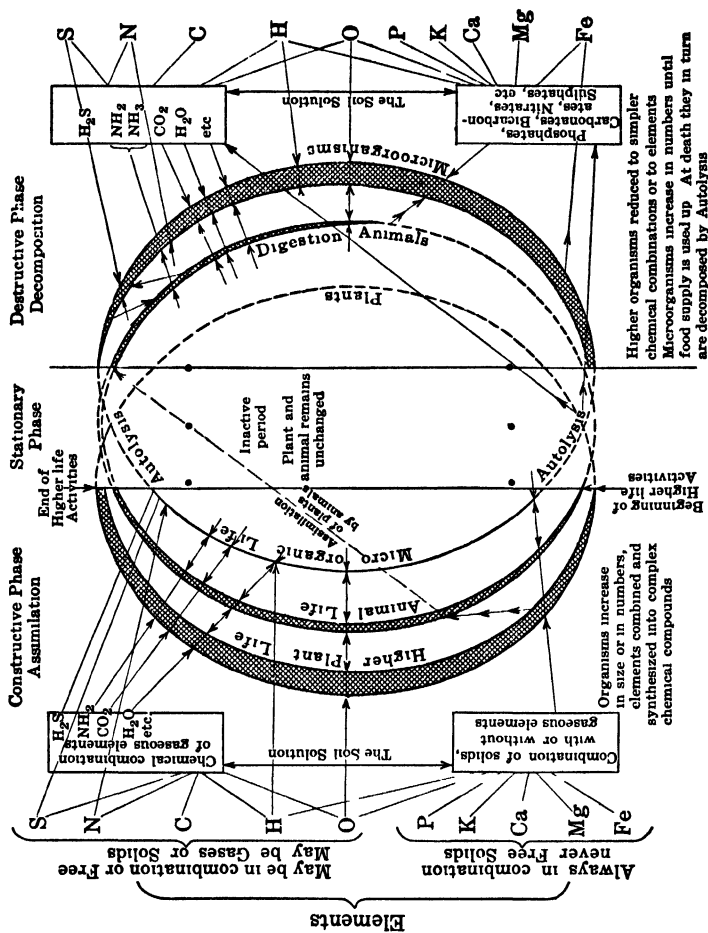



FIG 33—Cycle of elements essential in life processes.

ties, the other destructive. On the destructive side of the cycle they play a very important rôle, aided by the digestive processes of animals, in breaking down the complex combinations. In this phase of the cycle the higher plants have a questionable action, as indicated by the broken line. Animals play an insignificant rôle, while the micro-organism is all-important. The body of the micro-organism, however, is not of itself resistant to decomposition but, as indicated in the stationary phase, is reduced to the simplest combinations by the process of self-digestion, autolysis.

338. The Operation of the Cycle in Nature.—It appears that nature is opposed to the balancing of the cycle. That is, the amount of elements used in the constructive phase of the cycle may or may not be returned to the soil mass for the use of succeeding generations. This fact is graphically shown in Fig. 34. Thus carbon is assimilated from the atmosphere by plants and returned as carbon dioxide by the activities of micro-organisms. But plant remains may accumulate in the soil mass and undergo slow decomposition, or a large amount of carbon dioxide may be taken from the atmosphere and locked in the form of carbonate rocks. (Chamberlain estimates that the amount fixed by rocks annually is approximately 1,620,000,000 tons.) Some of this carbon dioxide is returned by decay and combustion processes. These processes tend to increase solubility and losses and removals by the action of moving waters, winds, etc. In fact,

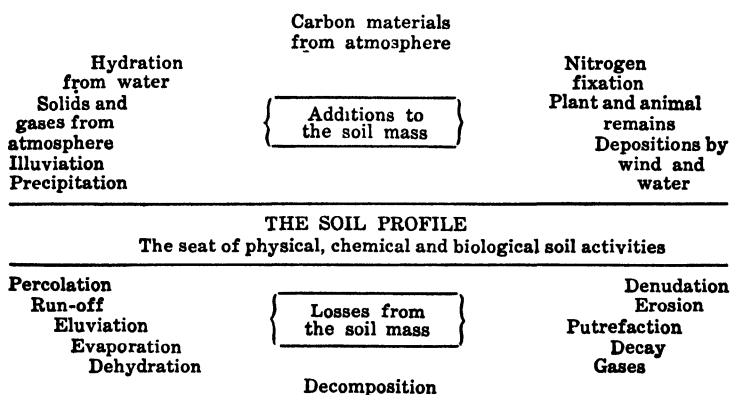



Fig. 34.—Progression of soil cycles in nature.

all the activities of nature tend to keep the elements essential to life on the move.

339. Effect of Man.—Possibly one of the greatest factors in the cause of an unbalanced condition of the cycle of elements is man. He removes the crops, in many cases wastefully destroys them, stimulates the solvent processes in the soil by tillage, allows the destructive forces of nature to operate unchecked, and in general depletes the crop-producing power of the soil. In this respect the relation of man toward nature is similar to that existing between two hives of bees of unequal strength. The stronger swarm of bees rob the weaker, but when the weaker find they are overcome they turn about and help in the robbing process. Nature acts in much the same manner. When a man robs the soil she willingly helps in the process, but the dissimilarity is seen in the results. Instead of depositing her spoils in the lap of the robber, nature takes them to parts unknown and thus leaves the owner in a poorer and poorer condition. In many cases it is possible, if the conditions of the soil itself are understood, to render unproductive areas productive or to increase the productivity of other areas.

APPENDIX

SOIL CHARTS

TABLES OF CHEMICAL AND MECHANICAL COMPOSITION OF SOILS

GLOSSARY

LENGTH OF SEASON WITHOUT KILLING FROST	LAND AREA, ACRES	PER CENT OF LAND AREA OF UNITED STATES
Under 90 days . .	179,127,000	9.4
90 to 120 days . .	308,375,000	16.2
120 to 150 days . .	357,039,000	18.8
150 to 180 days . .	317,831,000	16.7
180 to 210 days . .	317,610,000	16.7
210 to 240 days . .	221,063,000	11.6
Over 240 days . .	202,091,000	10.6

CHART 1.

AMOUNT OF PRECIPITATION	LAND AREA ACREAGE	PER CENT OF TOTAL LAND AREA OF U. S.
Under 10 inches . . .	153,634,432	8.1
10 to 20 inches . . .	588,775,719	30.9
20 to 30 inches . . .	314,258,301	16.5
30 to 40 inches . . .	320,089,545	16.8
40 to 50 inches . . .	324,846,189	17.1
50 to 60 inches . . .	160,366,829	8.4
60 to 80 inches . . .	28,898,105	1.5
80 to 100 inches . . .	9,430,528	0.5
Over 100 inches . . .	2,915,712	0.2

CHART 2.

CHART 3

WET, SWAMP, AND OVERFLOWED LANDS IN NEED OF DRAINAGE, 1920

State	Area unfit for cultivation without drainage, acres	Area in need of community drainage, acres	State	Area unfit for cultivation without drainage, acres	Area in need of community drainage, acres	State	Area unfit for cultivation without drainage, acres	Area in need of community drainage, acres
Ala. .	2,664,000	3,227,000	Ga. .	6,876,000	7,431,000	Me.	1,287,000	1,335,000
Ariz.	23,000	41,000	Idaho	97,000	141,000	Md.	499,000	607,000
Ark. .	4,220,000	4,881,000	Ill. .	600,000	2,340,000	Mass	135,000	172,000
Calif.	1,179,000	1,861,000	Ind. .	778,000	1,308,000	Mich.	5,111,000	5,671,000
Colo.	66,000	132,[illegible]	Iowa	368,000	919,000	Minn	5,909,000	6,757,000
Conn.	111,000	127,000	Kans	280,000	1,007,000	Miss.	4,752,000	5,648,000
Del. .	188,000	25[illegible],000	Ky. .	555,000	1,337,000	Mo. .	1,085,000	3,017,000
Fla. .	16,846,000	16,314,000	La. .	10,431,000	11,468,000	Mont	79,000	120,000

WET, SWAMP, AND OVERFLOWED LANDS—Cont.

State	Area unfit for cultivation without drainage, acres	Area in need of community drainage, acres	State	Area unfit for cultivation without drainage, acres	Area in need of community drainage, acres
Nebr. .	91,000	586,000	N. J. .	502,000	655,000
Nev. .	53,000	135,000	N. Mex	26,000	61,000
N. H. .	119,000	125,000	N. Y. .	815,000	1,091,000

WET, SWAMP, AND OVERFLOWED LANDS (Continued)

State	Area unfit for cultivation without drainage, acres	Area in need of community drainage, acres
N. C. .	5,390,000	5,806,000
N. Dak	137,000	953,000
Ohio. .	269,000	650,000
Okla. .	650,000	952,000
Oreg. .	650,000	2,790,000
Pa. . .	300,000	398,000
R. I. .	33,000	33,000
S. C. .	4,589,000	4,898,000
S. Dak	209,000	619,000
Tenn. .	669,000	1,066,000
Tex. .	6,824,000	7,709,000
Utah .	145,000	332,000
Vt. . .	73,000	88,000
Va. . .	1,038,000	1,496,000
Wash. .	689,000	908,000
W. Va.	74,000	244,000
Wis. .	4,046,000	5,122,000
Wyo. .	13,000	28,000
Total.	91,543,000	113,537,000

NATIVE VEGETATION
FOREST VEGETATION
CONIFEROUS FOREST
DECIDUOUS FOREST
MIXED FOREST
WOODLAND
(JUNIPER-PIÑON AND CHAPARRAL)
GRASS VEGETATION
TALL GRASS
(PRAIRIE GRASSLAND)
SHORT GRASS
(PLAINS GRASSLAND)
MESQUITE GRASS
(DESERT GRASSLAND)
DESERT VEGETATION
SAGE BRUSH
CREOSOTE BUSH
REPARED BY
R PHAEL ZON
U FOREST SERVICE
AND
L SHANTZ
UREAU OF PLANT
INDUSTRY

CHART 5

SOIL REGIONS
PREPARED BY
C.F MARBUT
AND
ASSOCIATES
IN THE
SOIL SURVEY
LIGHT COLORED SOILS
Brown gravelly and stony loams
Grayish to brownish silt loams and loams often poorly drained
Light brown predominantly silty loams from limestone drift
Gray to brown silty soils compact silty clay subsoils
Gray to brown soils heavy clay subsoils
Brown silt loams
Yellowish to reddish silt loams often stony
Yellowish silty, sandy to stony loams from sandstone
Reddish sandy and clay loams
Yellowish sandy loams
Yellowish silt loams
Yellow brown soils yellow subsoils
Red brown soils red subsoils
Light colored soils brown subsoils
DARK COLORED SOILS
Black soils highly calc. subsoils
Very dark brown soils calcareous subsoils
Dark brown silty soils yellowish brown subsoils
Dark brown loams yell. brown heavy subsoils
Dark brown soils clay subsoils
Black clays & clay loams from marly limestone
Dark colored calcareous soil poorly drained
Shallow, stony soils from limestone
Chestnut brown soils calcareous subsoils
Medium dark yellowish brown soils calcareous subsoils
OTHER SOILS
Brown soils of the Pacific Valleys
Gray or brown soils of arid regions
Sands & sands resting on clay in Florida
Alluvial soils
Marsh and Swamp
Rough and mountainous

Chart 6.

AVERAGE PRECIPITATION
BETWEEN APRIL 1 AND SEPTEMBER 30
PER CENT
UNDER 20
20 TO 40
40 TO 60
60 TO 80
OVER 80

CHART 7.

AGRICULTURAL REGIONS

REGION	LAND AREA, ACREAGE	LAND IN FARMS 1920		IMPROVED LAND IN FARMS 1920		LAND IN CROPS 1920	
		ACREAGE	P. CT. LAND AREA	ACREAGE	P. CT. LAND AREA	ACREAGE	P. CT. LAND AREA
Subtropical coast	61,500,000	12,965,000	21.1	5,111,000	8.3	3,728,000	6.1
Cotton belt	275,760,000	176,213,000	63.9	92,258,000	33.5	76,755,000	27.8
Corn and winter wheat region	201,087,000	156,712,000	77.9	99,239,000	49.4	69,438,000	34.7
Corn belt	145,987,000	135,572,000	92.9	113,166,000	77.5	89,668,000	61.4
Hay and pasture region	214,209,000	117,001,000	54.1	68,168,000	31.8	48,365,000	22.6
Spring wheat area	52,510,000	44,489,000	84.5	35,723,000	68.0	29,019,000	55.8
Great Plains region	304,837,000	193,369,850	63.4	52,285,000	17.2	36,006,000	11.8
Rocky Mountain region	146,101,000	24,159,000	16.5	6,930,000	4.7	4,465,009	3.1
Arid Intermountain Plateaus	341,704,000	59,817,000	17.5	15,760,000	4.6	9,226,000	2.7
North Pacific coast	71,766,000	12,219,000	17.0	3,519,000	4.9	2,264,000	3.5
South Pacific coast	38,032,000	22,044,000	57.9	10,246,000	26.9	5,945,000	15.6
Arizona-California desert	49,717,000	1,323,000	2.7	675,000	1.4	552,000	1.1
United States	1,903,215,000	955,884,000	50.2	503,073,000	26.4	375,432,000	19.7

CHART 9.

CHEMICAL AND MECHANICAL COMPOSITION OF SOME SOILS OF THE UNITED STATES AND CANADA

Data collected by Dr. C. F. Marbut and presented as an exhibit in "The Transcontinental Excursion" under the auspices of the American Soil Survey Association Descriptions, discussions, and interpretations of soils and soil relationships along the route of the excursion, following the First International Congress of Soil Science, Washington, D.C, 1927. Published by special permission.

Table I **Collington Fine Sandy Loam**

2 Miles southeast of Auburn, New Jersey Analyst: L. A. Denison

Constituents	0"–3"	3"–24"	24"–36"	36"–60"
CHEMICAL COMPOSITION:				
SiO_2	90.58	95.19	87.24	64.76
TiO_2	.56	.62	.50	0.67
Fe_2O_3	1.44	2.11	1.28	13.54
Al_2O_3	1.56	.50	7.10	9.30
MnO	.01	.01	.01	.035
CaO	.26	.31	.19	.04
MgO	.22	.18	.33	2.06
K_2O	.31	.22	.36	4.37
Na_2O	.38	.52	.56	.97
P_2O_5	.09	.09	.36	.11
SO_3	.22	.15	.21	.07
Ignition loss	4.96	.95	1.51	4.37
Total	100.59	100.85	99.65	100.29
N	.14	.05	.04	.01
CO_2 from carbonates	.00	.00	.00	.00
MECHANICAL COMPOSITION:				
Fine gravel	1.8	0.4	0.2	0.6
Coarse sand	7.6	9.0	7.4	9.3
Medium sand	17.6	22.6	18.6	13.8
Fine sand	53.1	54.6	47.7	30.4
Very fine sand	5.5	3.4	7.1	7.1
Silt	9.0	7.0	9.3	9.9
Clay	6.1	3.1	9.7	28.9
Total	100.7	100.1	100.0	100.0

Table II **Collington Loam**

1½ Miles north of Mulligan, Maryland Analyst: R. S. Holmes

Constituents	1"–12"	13"–18"	18"–40"	40"–45"
CHEMICAL COMPOSITION:				
SiO_2	87.98	87.08	77.71	77.65
TiO_2	.85	.92	.82	.47
Fe_2O_3	2.91	4.29	9.44	12.23
Al_2O_3	4.67	3.54	5.20	2.52
MnO	.01	.01	.01	.01
CaO	.21	.41	.30	.28
MgO	.32	.49	1.09	1.25
K_2O	1.45	1.62	2.91	2.51
Na_2O	.40	.40	.30	.30
P_2O_5	.09	.10	.12	.12
SO_3	.04	.05	.04	.24
Ignition loss	1.79	1.67	2.98	3.01
Total	100.72	100.50	100.92	100.33
N	.03	.02	.025	.02
CO_2 from carbonates	.00	.00	.00	.00
MECHANICAL COMPOSITION:				
Fine gravel	0.2	0.2	0.5	0.4
Coarse sand	3.7	4.0	4.4	11.0
Medium sand	6.2	6.4	5.8	18.9
Fine sand	51.8	49.8	45.4	49.9
Very fine sand	12.1	14.0	11.8	3.0
Silt	17.9	17.5	10.8	4.1
Clay	8.0	8.0	21.3	12.8
Total	99.9	99.9	100.0	100.1

Table III **Sassafras Gravelly Sandy Loam**

7 Miles south of Auburn, New Jersey

Constituents	0"–12"	12"–20"	20"–32"	36"–60"	At 60"
CHEMICAL COMPOSITION:		Analysts: G. Edgington, C. J. Hough			
SiO_2	84.29	85.52	59.57	42 27	76.32
TiO_2	0.54	0.54	0.80	0 43	0.20
Fe_2O_3	3.06	2.89	10.40	15.29	5.33
Al_2O_3	6.18	6 50	18.37	25.91	10.52
MnO	0.057	0.032	0.038	0.113	0.255
CaO	0.46	0.50	0 51	0.34	0.24
MgO	0.30	0.30	0 54	0.71	0.19
K_2O	1.26	1.28	2.26	2.58	2.59
Na_2O	0.52	0.52	0 21	0.41	0.27
P_2O_5	0.14	0.07	0.21	0.66	0.33
SO_3	0.08	0.03	0.12	0.12	0.07
Ignition loss	3.27	2 11	7.23	11.25	3.69
Total	100.14	100.29	100.26	100.08	100.01
N	0 08	0.025	0 035	0.038	0.011
CO_2 from carbonates	0.00	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				Analyst: A. A. White	
Fine gravel	6 6	1.9	6.8	14.6	36.3
Coarse sand	23.2	18.7	34.7	50.7	40.4
Medium sand	13.8	16 0	17.4	10.2	9.4
Fine sand	23.0	25 4	12.1	5 7	4 6
Very fine sand	10.4	9 1	2.2	0 7	0.3
Silt	19 9	19 0	7.9	4 5	2.2
Clay	3.0	9.5	19.0	13 7	6.7
Total	100.0	99.9	100.1	100 1	99 9

Table IV **Sassafras Sandy Loam**

Cabin Creek, Maryland Analysts C. J. Hough, S. Mattson, G. Edgington, I. A. Denison

Constituents	0"–2½"	4"–20"	20"–32"	33"–60"
CHEMICAL COMPOSITION:				
SiO_2	87.83	90.57	80.74	82.03
TiO_2	0 31	0 29	0 34	0.29
Fe_2O_3	1.76	1 11	2.25	2.25
Al_2O_3	3.92	4.77	10.58	8.57
MnO	0.006	0.006	0 01	0 006
CaO	0.24	0 16	0.74	0.76
MgO	0 11	0.14	0.26	0.20
K_2O	1 62	1.62	1.97	2.07
Na_2O	0.16	0.09	0.44	0.42
P_2O_5	0.03	0 02	0.08	0.07
SO_3	0.06	0 05	0.06	0.07
Ignition loss	3.87	1 45	3 67	3.01
Total	99.97	100.27	101.14	99.74
N	0.08	0.02	0.022	0.006
CO_2 from carbonates	0 00	0.00	0.00	0.00
MECHANICAL COMPOSITION:			Analyst: A. A. White	
Fine gravel	10 5	18 2	2.2	4.9
Coarse sand	36.1	46 8	16.6	30.2
Medium sand	15.3	13.4	14.3	19.6
Fine sand	20.9	13.4	41.6	26.0
Very fine sand	1.9	0.4	3.0	2.6
Silt	9.1	4.8	10.1	7.0
Clay	5.8	3.0	12.2	9.5
Total	99.9	100.0	100.0	99.8

Table V **Leonardtown Silt Loam**

Washington, D. C.

Constituents	¾" 4"	4" 18"	18" 28"	36+"
CHEMICAL COMPOSITION:			Analyst: G. J. Hough	
SiO_2	85.48	82.17	90.40	72.33
TiO_2	1.10	1.20	1.18	1.04
Fe_2O_3	2.10	3.74	2.42	5.75
Al_2O_3	6.23	8.14	3.60	13.87
MnO	0 02	0.018	0.016	0.008
CaO	0.60	0.44	0.32	0.37
MgO	0.34	0.63	0.42	0.43
K_2O	1.20	1.21	0.47	0.63
Na_2O	0.74	0.55	0.38	0.31
P_2O_5	0.07	0.12	0.05	0.08
SO_3	0.07	0.10	0.05	0.03
Ignition loss	2.82	2.84	1.36	5.25
Total	100.77	101 15	100.66	100.09
N	0.04	0.03	0.006	0.01
Co_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:			Analyst. A. A. White	
Fine gravel	0.0	1 1	2 1	3.2
Coarse sand	6.7	5.6	9.9	10.1
Medium sand	3 6	3.8	6.9	6.9
Fine sand	11.5	11.7	23.1	16.9
Very fine sand	12.8	12 0	20.2	11.4
Silt	53.2	29.5	21.9	11.8
Clay	12.0	36.3	15.8	39.8
Total	99.8	100.0	99.9	100.1

Table VI **Chester Loam**

2 Miles north of Rockville, Maryland

Constituents	0"-1"	1" 7"	7" 30"
CHEMICAL COMPOSITION:		Analyst. J. G. Smith	
SiO_2	66 40	66 99	62.56
TiO_2	1 12	1.00	1.04
Fe_2O_3	6.33	6.43	8.15
Al_2O_3	15 11	16.77	19.52
MnO	0.75	0.37	0.13
CaO	0.69	0.49	0.43
MgO	0.59	0.62	0.73
K_2O	2.69	3.24	3.28
Na_2O	0.60	0.51	0.57
P_2O_5	0.22	0.20	0.13
SO_3	0.15	0.10	0.08
Ignition loss	5.44	2.93	3.14
Total	100.09	99.65	99.76
N	0.21	0.10	0.04
CO_2 from carbonates	0.00	0.00	0.00
MECHANICAL COMPOSITION:		Analyst: A. A. White	
Fine gravel	8.2	1.0	1.6
Coarse sand	4.6	4.0	4.4
Medium sand	3.4	3.6	4.0
Fine sand	13.4	17.0	20.4
Very fine sand	8.2	12.4	12.0
Silt	38.6	42.2	34.3
Clay	23.6	19.9	23.3
Total	100.0	100.1	100.0

Table VII **Chester Loam**

Virginia Analyst: C. J. Hough

Constituents	½" 4"	12" 18"	30"–36"	45+"
CHEMICAL COMPOSITION:				
SiO_2	75.24	62.97	61.50	66.14
TiO_2	1.43	1.20	1.01	1.00
Fe_2O_3	4.19	6.75	7.94	6.94
Al_2O_3	11.09	17.92	19.20	16.85
MnO	0.05	0.03	0.05	0.06
CaO	0.20	0.24	0.20	0.20
MgO	0.52	0.89	1.08	0.96
K_2O	2.22	2.46	3.08	2.58
Na_2O	0.88	0.98	1.04	0.73
P_2O_5	0.06	0.08	0.10	0.08
SO_3	0.08	0.03	0.03	0.02
Ignition loss	3.83	6.06	5.10	4.31
Total	99.79	99.61	100.33	99.87
N	0.03	0.04	0.003	0.00
Co_2 from carbonates	0.00	0.00	0.00	0.00

Table VIII **Cecil Fine Sandy Loam**

Yadkin County, North Carolina Analyst: G. Edgington

Constituents	1"–7"	7" 14"	14" 40"	40+"
CHEMICAL COMPOSITION:				
SiO_2	87.13	69.49	34.24	49.62
TiO_2	0.54	0.85	1.31	0.80
Fe_2O_3	1.40	4.85	11.18	8.43
Al_2O_3	5.63	15.86	35.42	27.45
MnO	0.013	0.015	0.013	0.02
CaO	Trace	Trace	Trace	Trace
MgO	0 17	0.26	0.17	0.63
K_2O	2.05	1.52	0.62	2.08
Na_2O	1.41	1.16	0.73	1.04
P_2O_5	0 04	0.09	0.18	0.09
SO_3	0.13	0.13	0.10	0.12
Ignition loss	3.13	7.21	17.07	10.74
Total	101.45	101.26	101.06	101.06
N	0.07	0.06	0.04	0.02
Co_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				
Fine gravel	7.65	3.95	0.7	3.4
Coarse sand	13.8	9.6	3.2	6.8
Medium sand	7.1	5.0	1.8	3.0
Fine sand	37.1	22.7	6.4	15.4
Very fine sand	10.85	7.6	2.6	4.8
Silt	16.5	17.6	13.2	14.8
Clay	7.6	34.0	72.4	52.2
Total	100.6	100.4	100.1	100.4

Table IX **Cecil Sandy Loam**

Mt. Airy, Georgia

Constituents	0″–4″	6″–30″	40″–65″	About 75 ft.
CHEMICAL COMPOSITION:				Analyst: G. Edgington
SiO_2	83.19	75.58	74.59	75.41
TiO_2	0.91	1.05	0.68	0.81
Fe_2O_3	2.58	9.51	4.18	3.87
Al_2O_3	6.91	21.53	14.66	12.60
MnO	0.049	0.040	0.029	0.084
CaO	Trace	Trace	Trace	Trace
MgO	0.01	0.09	0.06	1.76
K_2O	0.56	0.80	0.82	2.89
Na_2O	0.06	Trace	0.06	0.19
P_2O_5	0.03	0.07	0.06	0.04
SO_3	0.04	0.11	0.04	0.05
Ignition loss	5.82	8.99	5.01	2.71
Total	100.16	99.77	100.19	100.41
N	0.079	0.018	0.005	0.001
Co_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				Analyst: A. A. White
Fine gravel	3.5	3.2	0.4	
Coarse sand	15.2	9.2	9.8	
Medium sand	11.8	5.5	11.4	
Fine sand	14.6	16.3	37.6	
Very fine sand	10.8	5.6	10.8	
Silt	30.3	21.5	22.4	
Clay	14.0	38.8	7.8	
Total	100.2	100.1	100.2	

Table X **Georgeville Silty Clay Loam**

[illegible] Miles southwest of Henrico, North Carolina

Constituents	2″–6″	6″–34″	34″–48″	48″–60″
CHEMICAL COMPOSITION:				
SiO_2	69.46	54.03	58.96	62.31
TiO_2	0.81	0.66	0.44	9.97
Fe_2O_3	5.10	8.30	7.52	6.11
Al_2O_3	15.09	25.97	22.44	20.26
MnO	0.02	0.013	0.013	0.004
CaO	0.04	0.30	0.14	0.22
MgO	0.21	0.23	0.21	0.38
K_2O	1.23	1.56	1.73	4.35
Na_2O	0.19	0.26	0.28	0.30
P_2O_5	0.08	0.13	0.14	0.13
SO_3	0.05	0.04	0.05	0.04
Ignition loss	7.40	8.86	7.53	4.67
Total	99.68	100.35	99.45	99.74
N	0.05	0.014	0.008	0.003
CO_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				Analyst: J. B. Spencer
Fine gravel	1.0	0.3	0.2	0.0
Coarse sand	1.9	0.9	0.8	1.4
Medium sand	1.4	0.6	0.7	3.4
Fine sand	21.7	11.2	19.3	50.0
Very fine sand	26.0	10.4	17.8	25.4
Silt	15.0	21.7	24.6	15.4
Clay	33.7	54.9	37.0	5.0
Total	100.7	100.0	100.4	100.6

Table XI Cecil Clay Loam

½ Mile northwest of Green Hill, North Carolina

Constituents	1"–6"	6"–40"	40–84"	84+"
CHEMICAL COMPOSITION:			Analyst: G. Edgington	
SiO_2	58.33	49.95	44.68	51.39
TiO_2	1.47	1.43	2.11	1.23
Fe_2O_3	6.38	9.31	11.36	5.56
Al_2O_3	20.06	26.54	27.68	24.72
MnO	0.056	0.040	0.095	0.123
CaO	Trace	Trace	Trace	1.03
MgO	0.58	0.45	1.30	1.43
K_2O	2.20	1.43	1.88	5.84
Na_2O	0.45	0.40	0.32	1.90
P_2O_5	0.10	0.04	0.18	0.64
SO_3	0.07	0.07	0.05	0.03
Ignition loss	10.79	10.63	10.59	5.63
Total	100.49	100.29	100.26	99.52
N	0.081	0.026	0.006	0.00
CO_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:			Analyst: A. A. White	
Fine gravel	2.8	2.1	1.0	5.0
Coarse sand	7.0	5.4	6.0	18.6
Medium sand	4.0	2.8	6.6	11.0
Fine sand	20.6	12.6	23.5	34.6
Very fine sand	9.6	8.0	9.9	8.0
Silt	28.6	24.7	21.8	14.1
Clay	29.5	44.1	31.3	8.7
Total	100.1	100.0	100.1	100.0

Table XII Iredell Loam

0.8 Mile east of West Bend, North Carolina

Constituents	0"–5"	5"–25"	25"+
CHEMICAL COMPOSITION:		Analyst: G. Edgington	
SiO_2	63.32	45.79	44.30
TiO_2	1.29	0.61	0.39
Fe_2O_3	12.19	10.93	10.25
Al_2O_3	9.30	24.70	19.27
MnO	0.358	0.121	0.175
CaO	3.11	1.97	7.62
MgO	4.75	3.96	12.21
K_2O	0.13	0.11	0.20
Na_2O	0.31	1.16	0.64
P_2O_5	0.01	Trace	Trace
SO_3	0.05	0.05	0.03
Ignition loss	5.25	11.00	5.02
Total	100.40	100.40	100.11
N	0.043	0.046	0.011
CO_2 from carbonates	0.00	0.00	0.00
MECHANICAL COMPOSITION:		Analyst: J. B. Spencer	
Fine gravel	10.7	0.5	0.6
Coarse sand	10.8	1.7	3.8
Medium sand	4.0	1.8	4.4
Fine sand	27.0	15.7	45.3
Very fine sand	22.4	11.4	23.3
Silt	18.1	18.2	16.2
Clay	6.9	50.4	6.4
Total	99.9	99.7	100.0

Table XIII Norfolk Sandy Loam

3 Miles north of Raiford, Georgia

Constituents	0"–7"	8"–12"	13"–18"	19"–30"	31"–70"
CHEMICAL COMPOSITION:				Analyst: J. B. Hough	
SiO_2	93.07	89.44	83.28	80.08	79.85
TiO_2	0.34	0.44	0.53	0.65	0.71
Fe_2O_3	1.10	2.07	3.20	4.0	3.20
Al_2O_3	2.27	4.97	8.35	11.35	10.42
MnO	0.05	0.03	0.01	0.005	0.005
CaO	0.60	0.30	0.60	0.36	0.30
MgO	0.14	0.06	0.08	0.08	0.12
K_2O	0.16	0.23	0.16	0.20	0.25
Na_2O	0.24	0.30	0.31	0.31	0.39
P_2O_5	0.09	0.05	0.06	0.05	0.07
SO_3	0.01	0.00	0.00	0.02	0.00
Ignition loss	2.07	2.46	3.80	4.22	4.54
Total	100.14	100.35	100.38	101.32	99.88
N	0.03	0.02	0.02	0.02	0.01
CO_2 from carbonates	0.00	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				Analyst: A. A. White	
Fine gravel	0.6	0.8	6.3		14.4
Coarse sand	4.6	8.0	40.4		50.1
Medium sand	5.7	6.4	22.2		21.6
Fine sand	41.4	33.6	21.6		12.1
Very fine sand	13.4	19.4	2.6		0.4
Silt	5.8	5.3	3.4		0.9
Clay	28.6	26.5	3.4		0.5
Total	100.1	100.0	99.9		99.9

Table XIV Tifton Fine Sandy Loam

½ Mile north of Laney, Georgia — Analyst: G. Edgington

Constituents	17"–46"	46"–72"	72"–90"	90"–110"
CHEMICAL COMPOSITION:				
SiO_2	52.28	73.76	75.35	73.68
TiO_2	0.69	0.66	0.71	0.69
Fe_2O_3	23.62	5.65	3.42	3.61
Al_2O_3	15.28	13.00	14.85	15.98
CaO	0.05	0.08	0.16	0.08
MgO	0.01	0.01	Trace	0.02
Ignition loss	7.22	5.55	5.22	5.65
H_2O at 110°	1.08	0.72	0.58	0.56

½ Mile south of Carnegie, Georgia — Analyst: J. B. Spencer

Constituents	0"–3"	4"–10"	11"–32"	33"–48"
MECHANICAL COMPOSITION:				
Fine gravel	2.4	1.1	1.0	0.9
Coarse sand	8.5	6.4	4.0	5.6
Medium sand	7.3	6.8	3.5	4.2
Fine sand	40.6	49.0	18.7	18.7
Very fine sand	17.4	14.5	11.0	10.7
Silt	10.1	16.0	21.4	11.3
Clay	13.7	6.5	40.4	48.5
Total	100.0	100.3	100.0	99.9

Table XV **Tifton Sandy Loam**

1½ Miles northeast of Meigs, Georgia

Analyst: G. J. Hough

Constituents	0″–4″	5″–11″	19″–33″	34″–39″
CHEMICAL COMPOSITION:				
SiO_2	91.81	94.01	77.26	76.94
TiO_2	0.38	0.38	0.72	0.66
Fe_2O_3	1.12	1.13	4.50	5.77
Al_2O_3	1.98	2.80	12.27	11.64
MnO	0.016	0.006	0.005	0.003
CaO	0.31	0.30	0.34	0.36
MgO	0.16	0.08	0.18	0.11
K_2O	0.15	0.16	0.20	0.19
Na_2O	0.19	0.10	0.30	0.24
P_2O_5	0.03	0.02	0.07	0.08
SO_3	0.01	0.02	0.03	0.06
Ignition loss	1.17	1.62	5.60	5.18
Total	100.68	100.92	101.17	101.23
N	0.10	0.02	0.031	0.02
CO_2 from carbonates	0.00	0.00	0.00	0.00

Analyst: J. B. Spencer

Constituents	0″–2″	3″–10″	11″–22″	22″–36″	37″–54″	55″–70″
MECHANICAL COMPOSITION:						
Fine gravel	2.5	4.1	2.3	1.6	1.4	2.6
Coarse sand	21.8	18.6	13.7	10.8	3.9	6.2
Medium sand	11.7	9.0	8.6	5.8	2.6	3.4
Fine sand	25.3	21.4	20.3	15.4	6.6	14.8
Very fine sand	3.9	4.1	4.6	6.3	3.0	10.0
Silt	23.5	32.2	26.6	23.7	25.7	18.6
Clay	11.2	7.0	23.8	36.4	57.7	41.5
Total	99.9	99.7	99.9	100.0	99.9	100.1

Table XVI **Decatur Silt Loam**

Montevallo, Alabama

Constituents	0″–3″	3″–13″	13″–29″	29″–36″
CHEMICAL COMPOSITION				
SiO_2	86.55	74.45	78.65	80.61
TiO_2	0.92	1.11	1.15	1.10
Fe_2O_3	2.22	4.30	4.96	4.21
Al_2O_3	5.27	11.29	10.16	9.03
MnO	0.02	0.02	0.02	0.02
CaO	0.20	0.11	0.06	0.07
MgO	0.06	0.24	0.21	0.26
K_2O	0.64	0.68	0.51	0.48
Na_2O	Trace	0.01	0.05	0.07
P_2O_5	0.06	0.12	0.06	0.05
SO_3	0.06	0.04	0.05	0.05
N	0.07	0.04	0.04	0.03
C	0.00	0.00	0.00	0.00

Table XVII Hagerstown Silt Loam

2½ Miles northeast of Ashwood, Tennessee

Constituents	0″–12″	12″–20″	20″–30″	30″–42″
CHEMICAL COMPOSITION:				
SiO_2	78.14	78.10	74.91	72.16
TiO_2	1.69	1.41	1.41	1.52
Fe_2O_3	3.61	3.59	4.39	5.82
Al_2O_3	7.24	9.14	12.13	13.18
MnO	0.35	0.41	0.31	0.57
CaO	0.86	0.66	0.48	0.49
MgO	0.26	0.37	0.16	0.52
K_2O	1.59	1.59	1.51	1.35
Na_2O	0.43	0.18	0.32	0.22
P_2O_5	0.31	0.31	0.36	0.55
SO_3	0.10	0.13	0.12	0.11
Ignition loss	5.17	4.25	3.82	4.57
Total	99.75	100.17	100.22	101.06
N	0.15	0.12	0.10	0.09
MECHANICAL COMPOSITION:			Analyst	A. A. White
Fine gravel	0.7	0.0	0.7	0.3
Coarse sand	1.5	1.7	2.6	3.4
Medium sand	0.5	0.6	0.7	1.3
Fine sand	1.1	1.3	1.4	2.3
Very fine sand	7.0	7.7	9.9	11.1
Silt	69.8	66.2	55.9	48.6
Clay	19.2	22.6	28.9	32.9
Total	99.8	100.1	100.1	99.9

Table XVIII Grenada Silt Loam

Rankin County, Mississippi — Analyst G. Edgington

Constituents	½″–7″	7″–20″	20″–35″	35″–60″
CHEMICAL COMPOSITION:				
SiO_2	85.39	74.00	80.80	87.19
TiO_2	0.82	0.85	0.79	0.86
Fe_2O_3	1.87	4.97	3.31	2.08
Al_2O_3	6.15	12.24	9.10	6.28
MnO	0.015	0.021	0.031	0.014
CaO	0.13	0.16	0.27	0.10
MgO	0.16	0.50	0.52	0.27
K_2O	1.37	1.53	1.27	0.63
Na_2O	0.80	0.85	0.87	0.40
P_2O_5	0.01	0.05	0.02	0.01
SO_3	0.02	0.02	0.03	0.05
Ignition loss	2.53	4.76	2.73	2.11
Total	99.57	99.95	99.77	99.99
N	0.018	0.029	0.013	0.005
CO_2 from carbonates	0.00	0.00	0.00	0.00

1 Mile north of Gloster, Mississippi — Analyst H. E. Middleton

Constituents	0″–6″	6″–18″	18″–36″
MECHANICAL COMPOSITION:			
Fine gravel	0.3	0.4	0.5
Coarse sand	0.8	0.9	2.4
Medium sand	1.0	0.7	1.7
Fine sand	2.1	1.8	3.3
Very fine sand	12.0	10.5	9.6
Silt	69.6	58.3	63.7
Clay	14.1	27.4	18.8
Total	99.9	100.0	100.0

Table XIX **Lebanon Silt Loam**

Constituents	0"–6½"	6½"–11½"	11½"–21"	21"–26"
CHEMICAL COMPOSITION :				
SiO_2	84.21	83.27	80.05	84.55
TiO_2	1.08	0.94	1.08	1.08
Fe_2O_3	2.74	2.26	2.42	2.84
Al_2O_3	5.79	7.89	10.13	7.25
MnO	0.11	0.06	0.05	0.03
CaO	0.29	0.25	0.15	0.13
MgO	0.20	0.27	0.45	0.31
K_2O	2.01	1.34	1.04	0.96
Na_2O	0.18	0.40	0.24	0.18
P_2O_5	0.09	0.08	0.03	0.06
SO_3	0.15	0.07	0.15	0.33
N	0.08	0.06	0.05	0.04

Table XX **Cherokee Silt Loam**

Cherokee County, Kansas

Constituents				
CHEMICAL COMPOSITION :				
SiO_2	86.96	85.13	69.30	67.82
TiO_2	0.69	0.74	0.71	0.72
Fe_2O_3	2.86	3.49	4.65	4.86
Al_2O_3	4.69	5.84	15.06	16.74
MnO	0.97	0.09	0.02	0.07
CaO	0.71	0.65	0.77	0.80
MgO	0.13	0.19	1.07	1.14
K_2O	0.91	1.00	1.20	1.11
Na_2O	1.07	1.16	1.10	1.04
P_2O_5	0.07	0.07	0.10	0.11
SO_3	0.08	0.07	0.18	0.23
N	0.113	0.09	0.131	0.089
Ignition loss	2.96	2.10	6.90	5.19

2 Miles southwest of Mineral, Kansas Analyst : W. B. Page

Constituents	0"–8"	8"–18"	18"–36"
MECHANICAL COMPOSITION :			
Fine gravel	0.3	0.8	0.0
Coarse sand	0.7	1.4	0.0
Medium sand	0.9	0.4	0.2
Fine sand	1.9	1.4	0.5
Very fine sand	8.2	8.1	3.2
Silt	84.3	81.2	46.9
Clay	4.4	6.6	49.1
Total	100.7	99.9	99.9

Table XXI **Grundy Silt Loam**

3 Miles west of Fairmount, Nebraska

Constituents	0"–6"	6"–15"	15"–36"	36"–44"	44"–60"
CHEMICAL COMPOSITION:			Analysts: G. J. Hough, G. Edgington		
SiO_2	71.47	71.54	65.13	70.08	68.45
TiO_2	0.61	0.67	0.62	0.58	0.59
Fe_2O_3	3.30	3.47	5.69	4.35	4.35
Al_2O_3	10.87	11.34	15.26	14.02	14.02
MnO	0.06	0.06	0.06	0.10	0.08
CaO	1.24	1.13	1.29	1.61	2.27
MgO	0.80	0.70	1.31	1.51	1.68
K_2O	2.39	2.22	2.03	2.53	2.51
Na_2O	1.36	1.22	1.14	1.37	1.44
P_2O_5	0.17	0.17	0.15	0.16	0.17
SO_3	0.08	0.08	0.08	0.04	0.07
Ignition loss	7.35	7.20	6.58	3.91	4.61
Total	99.70	93.60	100.26	103.26	100.24
N	0.21	0.20	0.10	0.058	0.031
CO_2 from carbonates	0.00	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				Analyst: J. B. Spencer	
Fine gravel	0.2	0.1	0.0	0.0	0.0
Coarse sand	0.3	0.2	0.1	0.0	0.1
Medium sand	0.1	0.2	0.0	0.0	0.1
Fine sand	1.7	1.2	0.1	0.3	0.4
Very fine sand	25.6	25.7	13.1	23.9	18.1
Silt	54.1	57.7	54.1	57.0	59.0
Clay	18.1	14.8	32.2	18.9	22.2
Total	100.1	99.9	100.2	100.1	99.9

Table XXII **Grundy Silt Loam**

20 Miles west of Lincoln, Nebraska

Constituents	0"–6"	6"–13½"	13½"–15"	15"–32"	33"–60"
CHEMICAL COMPOSITION:					
SiO_2	73.96	73.81	74.51	60.86	74.36
TiO_2	1.66	1.14	1.66	1.80	0.76
Fe_2O_3	2.12	2.50	2.74	3.63	3.72
Al_2O_3	9.61	10.54	10.72	22.85	12.29
MnO	0.01	0.05	0.04	0.04	0.091
CaO	0.82	0.81	0.77	0.96	0.82
MgO	0.33	0.37	0.41	0.71	0.82
K_2O	1.76	1.82	1.32	1.74	1.84
Na_2O	1.10	0.80	0.74	0.88	1.22
P_2O_5	0.22	0.24	0.13	0.31	0.03
SO_3	0.14	0.14	0.07	0.09	0.05
Ignition loss	...	...	...	...	4.34
Total	92.06	92.52	93.14	93.87	100.34
N	0.15	0.15	0.12	0.12	0.062
CO_2 from carbonates	0.00	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:				Analyst: Jacquot	
Fine gravel	0.0	0.0	0.0	0.0	0.6
Coarse sand	0.0	0.0	0.0	0.0	4.4
Medium sand	0.0	0.0	0.0	0.0	3.6
Fine sand	0.6	0.1	0.2	0.4	9.6
Very fine sand	23.1	22.2	20.8	17.8	12.0
Silt	61.9	64.1	61.2	49.5	45.6
Clay	14.3	13.5	15.2	32.1	24.3
Total	99.9	100.2	100.4	100.1	100.2

Table XXIII **Soil from Wellington, Kansas**

Constituents	29910* 0″–12″	29911* 12″–23″	29912* 24″–36″	29913* 36″–50″
CHEMICAL COMPOSITION:			Analyst:	G. J. Hough
SiO_2	71.60	74.28	70.67	70.93
TiO_2	0.81	0.81	0.74	0.77
Fe_2O_3	3.56	3.16	4.35	3.91
Al_2O_3	11.15	10.55	13.12	12.30
MnO	0.06	0.06	0.06	0.06
CaO	0.97	0.84	0.85	1.56
MgO	0.86	0.76	0.97	1.06
K_2O	2.42	2.43	2.32	2.43
Na_2O	1.04	1.08	0.92	1.07
P_2O_5	0.09	0.07	0.07	0.06
SO_3	0.11	0.08	0.04	0.04
Ignition loss	6.60	5.35	5.37	5.72
Total	99.57	99.77	99.48	99.91
N	0.09	0.12	0.07	0.05
CO_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:			Analyst:	J. B. Spencer
Fine gravel	0.0	0.0	0.0	0.0
Coarse sand	0.4	0.3	0.3	0.4
Medium sand	0.3	0.3	0.2	0.5
Fine sand	2.7	4.1	0.7	0.8
Very fine sand	4.3	15.2	16.1	7.7
Silt	57.5	49.9	38.3	50.2
Clay	31.4	29.5	44.2	40.1
Total	99.6	99.3	99.8	99.7

Table XXIV **Soil from Olmutz, Kansas**

Constituents	29888* 0″–4″	29889* 4″–22″	29890* 22″–32″	29891* 30′ +
CHEMICAL COMPOSITION:			Analyst:	G. Edgington
SiO_2	73.49	72.83	68.71	67.75
TiO_2	0.51	0.60	0.55	0.58
Fe_2O_3	2.72	3.08	4.22	3.93
Al_2O_3	10.83	12.00	14.66	13.83
MnO	0.063	0.072	0.069	0.073
CaO	1.27	1.16	1.37	2.03
MgO	0.71	0.86	1.58	1.59
K_2O	2.54	2.62	2.55	2.50
Na_2O	1.55	1.46	1.38	1.42
P_2O_5	0.13	0.12	0.11	0.13
SO_3	0.22	0.14	0.13	0.12
Ignition loss	5.81	4.99	4.29	4.71
Total	99.87	99.93	99.62	99.56
N	0.176	0.160	0.059	0.041
CO_2 from carbonates	0.00	0.00	0.00	0.00
MECHANICAL COMPOSITION:			Analyst:	J. B. Spencer
Fine gravel	0.0	0.0	0.0	0.0
Coarse sand	0.0	0.0	0.0	0.0
Medium sand	0.0	0.0	0.0	0.0
Fine sand	0.5	0.6	0.5	0.3
Very fine sand	30.5	35.2	26.8	21.4
Silt	45.1	35.0	28.9	37.7
Clay	23.8	28.9	43.5	40.3
Total	99.9	99.7	99.7	99.7

* U. S. Bureau of Soils numbers.

Table XXV Colby Silt Loam

¼ Mile southeast of Colby, Kansas Analyst: W. B. Pope

Constituents	0"-1½"	4"-5"	5"-9"	9"-40"
CHEMICAL COMPOSITION:				
SiO_2	72.91	70.11	60.69	62.64
TiO_2	0.53	0.52	0.49	0.52
Fe_2O_3	3.31	4.12	2.61	3.28
Al_2O_3	11.52	12.93	11.99	11.68
MnO	0.06	0.05	0.05	0.05
CaO	1.73	1.65	8.53	7.79
MgO	1.16	1.27	1.80	1.87
K_2O	2.23	2.41	2.52	2.57
Na_2O	1.27	1.61	1.45	1.47
P_2O_5	0.15	0.13	0.16	0.18
SO_3	0.11	0.15	0.12	0.11
Ignition loss	1.35	4.82	8.80	7.12
Total	99.33	100.1	99.24	99.28
N	0.16	0.18	0.14	0.10

Table XXVI Nevada Soil

12 Miles south of Ely, Nevada

Constituents	0"-1½"	1½"-4"	5"-15"	16"+
CHEMICAL COMPOSITION			Analyst: G. Edgington	
SiO_2	61.37	61.69	57.78	38.40
TiO_2	0.50	0.47	0.51	0.27
Fe_2O_3	3.81	3.87	3.67	2.09
Al_2O_3	13.89	13.77	12.85	7.57
MnO	0.155	0.118	0.095	0.05
CaO	3.82	5.48	8.61	24.35
MgO	2.61	2.60	2.50	2.40
K_2O	3.10	2.90	2.61	1.46
Na_2O	1.61	1.47	1.26	0.87
P_2O_5	0.21	0.18	0.15	0.14
SO_3	0.12	0.12	0.12	0.14
Ignition loss	6.08	7.62	9.99	21.98
Total	100.10	100.29	100.15	99.72
N	0.106	0.097	0.095	0.067
CO_2 from carbonates	1.65	3.00	5.12	18.55
MECHANICAL COMPOSITION:			Analyst: A. A. White	
Fine gravel	3.8	1.8	2.3	3.0
Coarse sand	5.1	1.8	6.1	10.4
Medium sand	2.1	2.8	1.0	5.6
Fine sand	10.5	11.8	11.8	19.7
Very fine sand	27.8	29.2	31.0	21.6
Silt	36.1	28.0	21.7	16.8
Clay	14.6	21.7	19.9	22.9
Total	100.0	100.1	100.1	100.0

Table XXVII **Colorado Soil**

From Cheyenne Wells, Colorado Analyst : C. J. Hough

Constituents	0″–2″	2″–8″	8″–24″	24″–40″
CHEMICAL COMPOSITION :				
SiO_2	72.70	64.60	57.80	63.70
TiO_2	0.45	0.487	0.343	0.427
Fe_2O_3	2.99	4.07	3.85	3.35
Al_2O_3	14.10	16.90	13.25	14.30
MnO	0.041	0.031	0.036	0.041
CaO	1.33	1.36	9.40	6.16
MgO	0.66	1.17	1.77	1.55
K_2O	1.49	2.59	1.68	2.20
Na_2O	2.86	3.36	2.62	2.30
P_2O_5	0.037	0.012	0.018	0.031
SO_3	0.173	0.188	0.121	0.051
Ignition loss	3.26	5.91	9.90	6.55
Total	99.99	100.7	100.8	100.7
N	0.074	0.116	0.069	0.017

Table XXVIII **Canada Soil**

From East Battleford, Canada

Constituents	0″–5″	8″–14″	14″–24″	24″–65″
CHEMICAL COMPOSITION :			Analyst .	G. Edgington
SiO_2	64.73	71.02	59.26	66.11
TiO_2	0.39	0.49	0.40	0.63
Fe_2O_3	3.22	3.49	3.28	6.18
Al_2O_3	9.76	11.27	9.95	14.17
MnO	0.147	0.085	0.063	0.048
CaO	1.70	2.27	8.40	1.97
MgO	1.00	1.38	3.13	2.19
K_2O	2.03	2.22	1.85	1.85
Na_2O	1.45	1.61	1.34	1.27
P_2O_5	0.17	0.13	0.14	0.08
SO_3	0.20	0.07	0.07	0.12
Ignition loss	15.55	6.12	12.11	4.85
Total	100.35	100.16	99.99	99.47
N	0.557	0.152	0.129	0.033
CO_2 from carbonates	0.00	1.01	7.72	0.85
MECHANICAL COMPOSITION :			Analyst :	Jacquot
Fine gravel	0.6	1.2	0.2	0.0
Coarse sand	3.1	3.4	1.8	0.1
Medium sand	2.0	2.2	1.1	0.1
Fine sand	11.0	8.2	5.5	15.0
Very fine sand	10.6	16.3	12.8	25.2
Silt	60.8	54.5	63.6	30.9
Clay	11.9	14.1	15.3	28.8
Total	100.0	99.9	100.3	100.1

Table XXIX **Canada Soil**

4 Miles southwest of Brooks, Canada

Constituents	0″–5″	5″–10″	10″–15″	10″–48″
CHEMICAL COMPOSITION:			Analyst:	G. J. Hough
SiO_2	79.47	72.06	69.33	72.16
TiO_2	0.44	0.53	0.45	0.45
Fe_2O_3	2.44	4.04	2.94	3.70
Al_2O_3	8.56	11.19	9.62	10.85
MnO	0.05	0.038	0.036	0.037
CaO	1.10	1.90	5.55	2.63
MgO	0.50	1 01	1.22	1.37
K_2O	1.62	1 82	1.60	1.75
Na_2O	2.40	2.14	2.19	1.90
P_2O_5	0.14	0.16	0.14	0.14
SO_3	0.07	0 07	0.13	0.50
Ignition loss	3.91	4.70	7.00	4.47
Total	100.70	99.66	100.20	99.95
CO_2 from carbonates	0.00	0 72	3.99	1.40
N	0.12	0 09	0.06	0 03
MECHANICAL COMPOSITION:			Analyst:	Jacquot
Fine gravel	1 2	0.5	0.6	1.6
Coarse sand	4.2	1 9	2.2	5.9
Medium sand	3.9	2 0	2.2	5.7
Fine sand	21.5	15.7	19.6	43 2
Very fine sand	29 9	23.0	23 3	25.9
Silt	30.9	35 3	33.1	10 0
Clay	8 4	21 6	19.2	7 8
Total	100 0	100 0	100.2	100.1

Table XXX **Canada Soil**

From Indian Head, Saskatchewan, Canada

Constituents	0″–4″	4″–20″	20″–30″	30″–66″
CHEMICAL COMPOSITION:			Analyst	G. J. Hough
SiO_2	60 51	66 21	59.51	52.40
TiO_2	0.52	0 52	0.51	0.68
Fe_2O_3	5.11	5.25	5.21	6 63
Al_2O_3	12.74	12 85	12.79	16.92
MnO	0.09	0 09	0.07	0.123
CaO	2.00	1.18	6.80	5.04
MgO	1.65	1 47	2.73	3.67
K_2O	2.17	2 20	1.77	2.30
Na_2O	0.79	0 96	0.89	0.79
P_2O_5	0.34	0.22	0 16	0.16
SO_3	0.20	0.09	0.07	0 15
Ignition loss	13.75	8 72	9.65	10.72
Total	99.87	100 06	100.16	99.58
N	0.43	0.23	0.05	0.05
CO_2 from carbonates	0.00	0.00	6.20	4.45
MECHANICAL COMPOSITION:			Analyst.	J. B. Spencer
Fine gravel	0.8	1.9	1.2	0.0
Coarse sand	2.3	7.6	6.1	0.3
Medium sand	1.9	5.0	4.3	0.2
Fine sand	9.5	11.7	11.6	0.9
Very fine sand	6.8	5 8	5.4	1.4
Silt	43.7	34.0	28.0	18.3
Clay	35.2	34.1	43.9	79.4
Total	100.2	100.1	100.5	100.5

Table XXXI **Miami Silty Clay Loam**

Marion County, Ohio

Constituents	0"–7"	7"–14"	14"–28"	28"–36"
CHEMICAL COMPOSITION:			Analyst:	G. J. Hough
SiO_2	74.61	65.18	62.88	56.53
TiO_2	0.84	0.91	0.85	0.66
Fe_2O_3	3.25	6.08	6.10	4.90
Al_2O_3	10.86	15.93	17.32	13.78
MnO	0.07	0.03	0.05	0.05
CaO	0.87	0.74	1.09	7.17
MgO	0.87	1.52	1.85	2.73
K_2O	2.19	3.10	3.39	3.02
Na_2O	1.52	1.19	1.17	1.09
P_2O_5	0.36	0.21	0.32	0.32
SO_3	0.09	0.08	0.09	0.06
Ignition loss	5.32	5.32	5.52	10.20
Total	100.95	100.29	100.63	100.51
N	0.15	0.08	0.08	0.07
CO_2 from carbonates	0.00	0.00	0.00	5.25
MECHANICAL COMPOSITION:			Analyst:	J. W. Bomboy
Fine gravel	0.6	0.1	0.2	1.0
Coarse sand	2.2	0.4	0.6	1.9
Medium sand	1.6	0.5	0.6	1.4
Fine sand	6.8	2.9	4.9	7.0
Very fine sand	8.8	5.6	5.9	8.6
Silt	59.8	47.2	46.4	48.4
Clay	20.2	43.1	41.6	31.8
Total	100.0	99.8	100.2	100.1

Table XXXII **Miami Silt Loam**

2 Miles north of Westport, Indiana

Constituents	0"–¾"	¾"–10"	10"–33"	34"–42"
CHEMICAL COMPOSITION:				
SiO_2	71.96	78.55	72.31	66.26
TiO_2	1.00	0.79	0.69	0.65
Al_2O_3	7.16	9.32	12.86	11.52
Fe_2O_3	2.71	2.77	4.57	5.06
MnO	0.10	0.08	0.10	0.08
CaO	1.41	0.72	1.11	4.15
MgO	0.57	0.60	1.03	2.72
K_2O	1.38	1.93	2.03	2.13
Na_2O	0.60	0.79	0.96	1.23
P_2O_5	0.28	0.18	0.19	0.32
SO_3	0.26	0.13	0.09	0.15
Ignition loss	11.75	4.00	3.57	5.69
Total	99.18	99.86	99.51	99.96
N	0.43	0.17	0.06	0.05
MECHANICAL COMPOSITION:				
Fine gravel	0.8	0.7	1.0	1.0
Coarse sand	4.0	2.6	2.4	3.8
Medium sand	2.0	1.8	2.6	4.0
Fine sand	8.2	6.9	15.3	24.8
Very fine sand	6.5	9.0	9.8	8.8
Silt	63.4	61.2	25.0	34.0
Clay	15.1	18.0	43.9	23.5
Total	100.0	100.2	100.0	99.9

GLOSSARY OF TERMS

The following glossary of terms is offered as an aid in explaining the various terms used in the text. The list includes terms that differ more or less from the usually accepted meaning, or that need more sharply defined soil application. Terms that are used in their usual (dictionary) meaning are not included. The majority of these terms have been taken from the report of the American Soil Survey Association, Committee on Terminology (*Bulletin 9*, 1928, pp. 23-58). The terms from this source are marked*.

**Abnormal Profile*.—A profile departing from the normal, typical or regional profile conditions in some important respects, by reason of some unusual change in the factors governing weathering. Abnormal profiles might be caused by excessive erosion following the removal of vegetative cover, by changes in drainage conditions due to natural or artificial causes, or by any circumstance which might alter the natural conditions governing weathering. See *Profile.*

Absorption.—The taking up or in by chemical or molecular action. Engrossing completely.

**Acid Soil.*—A soil that is deficient in available bases, particularly calcium, and which gives an acid reaction when tested by standard methods. There is no full agreement on the most satisfactory test for "acidity," and field tests are made by the use of various convenient indicators. The intensity or degree of acidity can be expressed by the qualifying words—strongly, moderately, etc.

Acidoid.—A colloidal substance which has the chemical characteristics of an acid, yet produces no discrete but only colloidal ions. Distinctive from a truly soluble acid.

Adhesion.—The union of materials of unlike characteristics. The particles are attached more or less firmly together by their adjacent surfaces. A degree of cementation. The process is analagous to cohesion. See *Cohesion.*

**Adobe.*—A soil which on drying cracks and breaks into irregular but roughly cubical blocks. The cracks are usually wide and deep and the blocks from twenty to fifty or more centimeters across. (Adobe soils are usually heavy-textured and high in content of colloidal clay.) See *Soil Structure.*

Adsorption.—The phenomenon where some substance, homogeneously dissolved in a phase, accumulates at the boundary layer to a higher

concentration or aims at some regular arrangement of its molecules in the boundary layer.

**Aeolin Soil.*—Soil formed from materials transported and deposited by wind. The group includes not only the areas of wind-blown sands usually associated with sand dunes, but also the large areas of wind-borne fine-textured materials such as the loessial deposits or the wind-modified deposits of fine volcanic ash. See *Transported Soils.*

**Aged Soil (Solum Annosum).*—A soil in which a fully matured soil profile is again being subjected to modification, due to changes in the environmental conditions or weathering forces. *Aged or degenerated* soils are usually the result of changes in environmental condition involving vegetation, drainage, or climate. This term is inaccurate as such soils are actually starting on a new cycle of development, under changed or changing conditions of environment. See *Soil Development.*

Aggregation—Aggregates.—The tendency of soil particles to gather together in clumps or aggregates. The process may be due to a sticky condition induced by the colloid, to cementing materials, to coagulation, or to flocculation. The degree of aggregation markedly influences the structural characteristics of the soil.

**Alkali Soil—Alkali.*—A soil containing *any* soluble salts in sufficient amount to cause injury to economic plants. See *Saline Soil.*

**Alkaline Soil.*—A soil containing an excessive amount of the alkaline (in true chemical sense) salts, usually sodium carbonate. See *Saline Soil.*

**Alluvial Soil.*—Soil formed from materials transported by flowing waters and deposited as alluvial fans and flood plains. See *Transported Soils.*

**Amorphous.*—A soil of fine texture having a massive or uniform arrangement of particles throughout the horizon. Structureless. Only found in soils of high colloidal content and of the finest texture, where individual grains can not be recognized. See *Soil Structure.*

Available.—A condition of the soil constituents in relation to plants. Compounds or elements, in such form of combination and under such soil conditions as to become quickly assimilated by growing plants. See *Plant Food Element.*

Binding Power.—The resistance of the soil mass to rupture. Usually measured by the force required to cause an instrument of standard size to penetrate the soil mass. A result of cementation.

**Brittle.*—A soil which when dry will break with a sharp, clean fracture. If struck a sharp blow, it will shatter into cleanly broken hard fragments. See *Soil Consistence.*

**Buckshot.*—Aggregates of roughly spherical shape, usually two or three millimeters in diameter, and of a hard consistence. See *Soil Structure.*

**Calcareous Soil*.—A soil containing sufficient calcium carbonate to effervesce when tested with weak (0.1N) hydrochloric acid. In accordance with the amounts present, these soils may be designated as slightly calcareous, strongly calcareous, etc.

**Cellular*.—A soil having pore spaces of more or less regular size and shape interconnected throughout the entire soil mass. See *Soil Porosity*.

**Cemented—Cementation*.—A condition occurring when the soil grains or aggregates are caused to adhere firmly and are bound together by some material that acts as a cementing agent (as colloidal clay, iron, silica, or aluminum hydrates, lime carbonate, etc.). See *Soil Consistence*.

The degree of cementation or the persistence of the cementation when the soil is wetted should be stated. Some terms indicate the degree of relative permanence, as—indurated, hardpan, etc. The degree of cementation is usually as follows:—

1. *Firmly Cemented*.—Cementing material of considerable strength, requiring considerable force to rupture the mass. Usually breaks with clean but irregular fractures, into hard fragments.
2. *Weakly Cemented*.—Cementing material is not strong, and the aggregates can be readily broken into fragments with a more or less clean fracture.
3. *Softly Cemented*.—Cementing material is not strong nor evenly diffused throughout the mass. Aggregates are readily crushed, but do not break with a clean fracture.
4. *Indurated*.—A soil cemented into a very hard mass that will not soften or lose its firmness when wet, and which requires much force to cause breakage. Rock-like.

Cheesy.—A soil having a more or less elastic character, deforming considerably without rupture, yet broken without difficulty or the application of much force. Characteristic of certain highly colloidal soils when thoroughly wet. See *Soil Consistence*.

Class of Soil.—See *Textural Grade*.

Classification.—For the various soil groupings, see *Phase; Soil Family; Soil Province; Soil Series; Soil Type*.

Clay.—See *Soil Texture; Textural Grade; Texture*.

Clay Loam.—See *Textural Grade; Texture*.

**Claypan*.—An horizon of accumulation or a stratum of stiff, compact, and relatively impervious clay.

The claypan is not cemented, and if immersed in water can be worked to a soft mass. Its presence may interfere with water movement or root development as does a true hardpan. It is more difficult to overcome, for whereas a hardpan can be shattered by explosives, the claypan, after breaking by any means, will run together and reform as soon as thoroughly wetted. The distinction between the hardpan and the claypan is an important one in the soil classification.

**Clod* (*or Cloddy*).—Aggregates of irregular, angular shape, usually eight centimeters or more in diameter and of a hard consistence. See *Soil Structure*.

Fine Cloddy.—When most of the clods are close to the minimum size. (Eight to twelve centimeters.)

Coarse Cloddy.—When most of the clods are 20 centimeters or more in diameter.

Coagulation.—The process of changing separates, sols, gels, suspensoids, etc., into a clot or an aggregate. A process of flocculation.

**Coastal Beach*.—Shelving and sloping beaches of sand, gravels, shingle or stone, swept by waves in time of storms and high tides. Often includes areas of low sand dunes.

Coherent.—Relative degree of compactness can be expressed by terms as—slightly compact, very compact, etc. See *Soil Consistence*.

Cohesion.—The union of materials of like characteristics, forming a mass that resists a force tending to disrupt it. A degree of cementation.

**Colloidal Soils*.—Soils in which particles exhibiting colloidal characteristics are present in sufficient amount to have an appreciable effect on the soil character.

**Columnar*.—A natural arrangement of the soil mass in more or less regular columns separated by vertical cleavage planes, and usually broken by horizontal cracks into sections with longer vertical than horizontal axes.

Prismatic Columnar.—Columns broken into sections quite regular in size, parallel faced, with the vertical axes much longer than the horizontal axes. Usually pentagonal or hexagonal.

Jointed Columnar or Jointed.—Columns broken into sections having the vertical and horizontal axes nearly equal. See *Soil Structure*.

**Compact*.—A soil that is dense and firm, but without any cementation. Quite resistant to forces tending to cause rupture or deformation.

Conduction.—The transmission of heat, sound or electricity through matter without motion of the affected body as a whole. Distinguished from convection and radiation. In the soil mass, heat is transferred from one body to another or from one part of the body to another part. The transference is by contact and a stimulation of molecules in the conducting substance.

Conductivity.—The quantity of heat in calories which passes across a cube of unit edge (1 cm.) in unit time (1 second) under a uniform temperature gradient of one degree Centigrade per centimeter.

Consistent. See *Soil Consistence*.

Convection.—The conveying; diffusion of heat through a liquid or a gas by motion of its parts. In the soil mass, the transference is primarily by means of gases moving from more concentrated to less concentrated areas.

**Crumb-Structure*.—Porous aggregates of irregular shape, rarely over two centimeters in diameter and of a *medium* to *soft* consistence.
Fine Crumb.—Crumbs five millimeters or less in diameter.
Coarse Crumb.—Crumbs two centimeters or more in diameter. See *Soil Structure*.
**Crust (or Crusted)*.—Where the upper or surface horizon coheres into plate or crust distinct from the horizon immediately below it. See *Soil Structure*.
**Crust Mulch*.—An arrangement where a surface crust is underlain by an horizon of loose, incoherent particles of mealy, crumb, or granular structure. See *Soil Structure*.
**Cumulose Soil*.—Sedentary soils formed by the accumulation of more or less decayed organic remains. Organic soils. See *Soil Genesis*.

Degenerated.—See *Aged Soil*.
**Dense*.—A soil mass in which a relatively small proportion of the total volume consists of pore spaces, with an absence of any large pores or cracks. See *Soil Porosity*.
Diffusion.—The tendency of materials to move from higher to lower concentration. The spontaneous intermingling of the molecules of two phases. Distinguished from mixture by mechanical force or by the action of gravity. Usually applied to the movements of the gaseous phase of the soil mass.
Diggings.—See *Hydraulic Diggings; Placer Diggings*.
Dispersion.—The act of separation in all directions.
**Dunesand*.—Areas of wind-drifted sand in dunes, hummocks, and ridges, usually free from vegetation and undergoing active erosion and re-deposition by winds.

**Edaphologist (or Edaphist)—Pedologist*.—One versed in Edaphology or engaged in the study of the soil. A soil scientist.
**Edaphology (Pedology)*.—That branch or department of science which deals with the soil as a natural body. Edaphology deals particularly with the soil as a natural body and in its natural position, but includes also studies of soil chemistry, soil physics, soil biology, and other lines of investigation where the aim is an elucidation of soil problems. The term Pedology (or Pedologie) has already been appropriated by an organization dealing with children and can not properly be used in the English-speaking countries.
Elasticity.—The ability to stretch and return to normal, elastic. Possessed by the soil mass in varying degrees. A property usually imparted to the soil mass by organic matter and by colloids.
**Eluviation—Eluvial*.—A process of removal by percolating waters of material in solution or in suspension. Horizons from which material has been removed by eluviation. See *Horizon A*.

Family.—See *Soil Family*.
Fertility.—See *Soil Fertility; Soil Productivity*.

**Firm.*—A soil resistant to forces tending to produce rupture or deformation. Moderately hard. Aggregates can be broken between fingers. See *Soil Consistence.*

Flocculation.—The coagulation and aggregation of soil particles due to physical and chemical action. Usually a result of the electrical charge. A process in the formation of granules.

**Floury.*—Fine-textured soil consisting predominantly of silt (or flocculated clay with aggregates of silt size) which when dry is incoherent, smooth, and dust-like.

**Fluffy.*—A surface condition where the aggregates are loose, of light weight and fine texture, with no cohesion or evidence of arrangement; floury. See *Soil Structure.*

Fraction.—See *Soil Separate.*

**Friable.*—A soil with aggregates that can be readily ruptured and crushed with application of moderate force. Easily pulverized or reduced to crumb or granular structure. See *Soil Consistence.*

Genesis.—See *Soil Genesis.*

**Glacial Soil.*—Soil formed from materials transported and deposited by glacial action. These include the till, moraine, drumlin, kame and kettle, oskor, and other typical forms, and a portion of the loessal deposits. See *Transported Soils.*

Grade.—See *Separate.*

**Granular.*—Aggregates varying in size to two centimeters in diameter, of medium consistence, and more or less subangular or rounded in shape. See *Soil Structure.*

Fine Granular.—Aggregates under five millimeters diameter.

Coarse Granular.—Aggregates close to maximum size.

Granulation—Granules.—The cementation of particles into masses as grains, aggregates, or clumps. A more or less permanent result of flocculation and aggregation. The granules may be of various size and shape.

Gravel, fine.—See *Soil Texture.*

Gravelly.—See *Texture.*

**Gritty.*—Containing a sufficient amount of angular grains of coarse sand or fine gravel so that these dominate the "feel." Usually applied to medium-textured soils (loams) where the actual quantity of these coarse grains is quite small.

**Hard.*—A soil resistant to forces tending to cause rupture or deformation. Difficult or impossible to crush aggregates with fingers only See *Soil Consistence.*

**Hardpan.*—An horizon of accumulation that has been thoroughly cemented to an indurated, rock-like layer that will not become soft when wet. The true hardpan is cemented by materials that are not readily soluble, and is a *hard* layer that (except where fractured or

cracked) definitely and permanently limits downward movement of roots and water. The term "hardpan" is not properly applied to hard clay layers that are *not* cemented, nor to those layers that may seem indurated when dry but which soften and lose their rocklike character when wet. Immaturely developed soils may have a hardpan-like horizon which, while partly cemented, has not reached a true permanent hardpan state. In ordinary practice, these are considered as hardpans, being described as "immature hardpans" or as "soft hardpans." See *Claypan.*

**Heavy.*—Applied to soils of fine texture in which clay predominates, with dense structure and firm to compact consistence. The term is also applied to soils containing a somewhat higher proportion of the finer separates than is typical of that textural grade (as a "heavy sandy loam").

**Honeycomb.*—A natural arrangement of the soil mass in more or less regular five- or six-sided sections separated by narrow or hairline cracks. Usually found as a surface structure or arrangement. See *Soil Structure.*

**Horizon—Soil Horizon.*—A layer or portion of the soil profile, more or less well defined, and occupying a position approximately parallel to the soil surface. See *Horizon A, Horizon B, Horizon C; Profile; Stratum; Substratum; Subsurface; Subsoil.*

**Horizon A.*—The upper horizon of the soil mass, from which material has been removed by percolating waters. The eluviated horizons of the solum. The "surface" soil. This horizon is generally subdivided into two or more sub-horizons, of which A_0 is not a part of the mineral soil, but is the accumulation of organic débris upon the soil surface. Other sub-horizons are designated as A_1, A_2, etc. See *Horizon.*

**Horizon B.*—The horizon of deposition, to which materials have been added by percolating waters. The illuviated horizons of the solum. The "subsoil." This horizon may be divided into several sub-horizons, depending on the color, structure, consistence, or the character of the material deposited. These sub-horizons are designated as B_1, B_2, B_3, etc. See *Horizon.*

**Horizon C.*—The horizon of relatively unweathered material underlying the B Horizon. The "substratum." The C Horizon, while often described as "unweathered," usually shows some modification in the upper portions and may have one or more sub-horizons. In most cases, it represents the "parent material" similar to that from which the soil was formed. In some cases, a stratum or geological formation of material different from that of which the soil was formed may underlie the solum. With such conditions, there is actually no true C Horizon, the B Horizon resting directly on unrelated material. In actual practice, however, this is usually called the C Horizon, its character and lack of relation to the solum being brought out in the descriptions. See *Horizon.*

**Humus.*—A more or less stable stage in the decomposition of organic matter in the soil. This term is quite indefinite in application and also in an analytical sense. It is better to use the more general term "organic matter" when referring to the organic content of the soil.

**Hydraulic Diggings.*—Areas from which soil and substratum have been washed by hydraulic mining operations—usually occurs as extensive erosion scars.

**Illuviation—Illuvial.*—A process of accumulation by deposition from percolating waters of material transported in solution or suspension. Horizons in which material has been deposited by illuviation. See *Horizon B.*

Imbibition.—The absorption and holding of water by the soil mass.

**Immature Soil (Solum Immaturum).*—A soil having a profile with compact subsoil horizons with distinct clay accumulations; moderately weathered immature soil. See *Soil Development.*

**Impervious.*—A soil very resistant to penetration by water and usually to air and to plant roots. Impenetrable. In field practice the term is applied to strata or horizons that are very slowly penetrated by water and that retard or restrict root penetration. "Relatively impervious" or "Slowly impervious" are better expressions. See *Soil Consistence.*

Indurated.—See *Cemented.*

Jointed.—See *Columnar.*

**Lacustrine Soil.*—Soil formed from materials deposited by the waters of lakes and ponds. See *Transported Soils.*

**Laminated.*—An arrangement of the soil in very thin plates or layers, less than one millimeter in thickness, lying horizontally or parallel to the soil surface. Usually fragile and of medium to soft consistence. See *Soil Structure.*

Layer.—See *Soil Layer; Horizon.*

**Light.*—Applied to soils of coarse to medium texture with very low silt and clay content, incoherent, single-grained structure, and loose consistence. The term is also applied to soils containing somewhat higher proportions of the coarser separates than is typical of that textural grade (as a "light loam").

Loam.—See *Texture.*

Loamy Sand.—See *Textural Grade.*

**Loessal Soil.*—Soils formed from transported materials deposited as loess. See *Transported Soils.*

**Loose.*—A soil with particles or small aggregates that are independent of each other or are weakly cohering, with a maximum of pore space and a minimum resistance to forces tending to cause rupture. See *Soil Consistence.*

**Lump* (*Lumpy*).—Aggregates of irregular shape, of medium to hard consistence, and from two to ten centimeters in diameter.

Fine Lumpy.—Aggregates below three centimeters in diameter.

Coarse Lumpy.—Aggregates over six centimeters in diameter. See *Soil Structure*.

**Madeland*.—Areas of artificial fills of soil material more or less mixed with waste, refuse, and débris.

**Marine Soil*.—Soil formed from materials deposited by the waters of oceans and seas, exposed by elevation of the land or the desiccation of the sea. The lacustrine and marine deposits may be the coarser sediments of beaches and bars or the finer sediments of exposed areas of lake or sea beds. See *Transported Soils*.

**Marsh*.—Flat, wet, treeless areas usually covered by standing water and supporting a native growth of coarse grasses, reeds, or rushes.

**Massive*.—A soil mass showing no evidence of any distinct arrangement of the soil particles. Structureless. May be found in soils of any texture. See *Soil Structure*.

**Mature Soil* (*Solum Maturum*).—A soil having a profile with a compact highly colloidal dense clay horizon or with a cemented rock-like hardpan horizon; fully weathered mature soil. The end-product of weathering under the existing conditions. A climax soil. *Mature* soil development presupposes the absence of severe erosion, changes in drainage, changes in vegetative cover or other modifications of conditions that would affect the characteristic weathering under the prevailing climate of the region. These soils have existed under the given conditions for a period of time long enough to have approximated full adjustment with the weathering forces. See *Soil Development*.

**Mealy*.—A crumb-like structure where the aggregates are of soft to very soft consistence and usually less than five millimeters in diameter. See *Soil Structure*.

**Mellow*.—A soil with particles or aggregates that are weakly adhering in a rather porous mass, readily yielding to forces causing rupture. A consistence softer than friable. Without tendency to pack. See *Soil Consistence*.

**Mineral Soils*.—Soils composed mainly of inorganic (mineral) material containing relatively low quantities of organic material. See *Soil Genesis*.

Moisture-Holding Capacity.—The ability of the soil mass to hold or retain water against the natural force of gravity.

**Muck Soil*.—Soil composed of thoroughly decomposed organic material, with a considerable amount of mineral soil material, finely divided and with few fibrous remains.

**Mulch* (*or Mulched*).—An horizon with a loose, incoherent arrangement of aggregates of mealy, crumb, or granular structure. See *Soil Structure*.

**Normal Profile.*—A characteristic profile developed under conditions of weathering that have remained relatively uniform throughout the period of profile development. See *Profile.*

**Nut Structure.*—Compact aggregates, more or less rounded in shape, of hard to medium consistence, and usually from one-half to four centimeters in diameter. See *Soil Structure.*

**Old Valley-Filling Soils—Old Transported Soils.*—Weathered secondary (transported) soils. See *Transported Soils.*

**Organic Matter (of the Soil).*—The more or less decomposed material of the soil derived from organic sources, usually from plant remains. The term "organic matter" covers such material in all stages of decay and is recommended as a better term than "humus," which, though in general use, is indefinite and poorly defined.

**Organic Soils.*—Soils composed mainly of organic material; the organic content being sufficient to dominate the soil characteristics. See *Soil Genesis.*

**Parent Material.*—The slightly altered or wholly unweathered material beneath the solum, similar to that from which the soil was formed. The C horizons. See *Horizon C.*

**Peat Soil.*—Soil composed predominantly of organic material, considerably decomposed but highly fibrous, with easily recognizable plant remains.

Pedology.—See *Edaphology.*

Percolation.—The act of water filtering through the soil mass. A result of permeability. See *Eluviation.*

Permeability—Permeable.—The condition of the soil mass that allows the more or less free passage to liquids or gases. Porous.

**Phase.*—A subdivision of the *soil type* covering departures from the typical soil characteristics, insufficient to justify the establishment of a new type, yet worthy of recognition. The *Phase* subdivision is used when the deviation from the typical may be insufficient to warrant the establishment of a new type, or when the areal extent of a major variation is too small to warrant its independent recognition, yet where it is desirable to show the location and extent of the typical material on the map and in the report. Phase variations may cover color, texture, structure, topography, drainage, or any other feature of deviation from the typical. See *Classification.*

**Placer Diggings.*—Areas where placer mining has overturned or removed the soil and left a rough, eroded, and scarred surface of little or no agricultural value.

Plant Food.—The material manufactured by the plant itself for its nourishment and growth. The manufacturing process consists of changing the plant food elements from the inorganic to the organic

state. As the manufactured product contains energy it is spoken of as *synergic plant food.* This form of food is assimilated by the plant without it leaving the organism. The plant apparently cannot assimilate synergic plant food material that is outside its body. Distinguished from *Plant Food Element,* which see.

Plant Food Element.—Any element, singly or in combination, entering plant tissues, which later may be profitably used in the manufacture of plant food. Such elements or combinations are incapable of furnishing energy to the higher plants. They are frequently classified as *anergic plant food.* Distinguished from *Plant Food,* which see. A plant food element may be *soil-derived* (obtained from the soil mass) or *air-derived* (obtained from the atmosphere). It may be in various stages of availability. See *Available, Potentially Available, Unavailable.*

**Plastic.*—A soil readily deformed without rupture. Pliable but cohesive. Can be readily molded. Putty-like. See *Soil Consistence.*

**Plate (or Platy).*—An arrangement of the soil mass in plates or layers one to five millimeters or more in thickness, lying horizontal or parallel to the soil surface. Usually of medium to hard consistence. See *Soil Structure.*

**Porosity.*—See *Soil Porosity.*

**Porous.*—A soil mass in which a large proportion of the total volume consists of voids or pore spaces. See *Soil Porosity.*

Potentially Available.—A condition of the soil-derived plant food elements as measured by plant growth. Compounds or elements in such form of combination and under such soil conditions as to become available during the growing period of a plant. See *Plant Food Element.*

**Primary Soils.*—Soils developed through the disintegration and decomposition of rocks in place and the weathering of the resulting débris to true soils with definite horizons of eluviation and illuviation. Residual soils. See *Soil Genesis.*

Prismatic.—See *Columnar.*

**Profile—Soil Profile.*—A soil profile is a vertical section of the soil from the surface into the underlying unweathered material. See *Abnormal Profile; Normal Profile; Regional Profile; Typical Profile; Horizon.*

Province.—See *Soil Province.*

**Puddled.*—A condition of massive structure brought about when by artificial or natural action the previously existing structures are broken down and destroyed. Deflocculated. See *Soil Structure.*

**Pulverent.*—The soil reduced to a mass of soft crumbs and granules. See *Soil Structure.*

Radiation.—The propagation of heat as a free wave motion in the ether without permanently affecting the intervening space between the radiating body and the body receiving the radiant energy. The

soil mass absorbs a portion of the radiant energy of the sun, reflecting the balance. Later, the absorbed heat may be again liberated by radiation into the atmosphere.

**Recent Soil (Solum Crudum).*—A soil having a profile without definite horizons of eluviation or illuviation; relatively unweathered recent or very immature soil. Recent soils usually are secondary soils composed of recently deposited transported materials, there being no evidence of any downward migration of clay, lime, or other material, no evidence of difference in the degree of weathering of the minerals at any varying depths, and no indication of any changes in structure of the soil. See *Soil Development.*

**Recent Valley-Filling Soils—Recent Transported Soils.*—Unweathered secondary (transported) soils. See *Transported Soils.*

**Regional Profile.*—A generalized description giving the profile characteristics common to the soils of a broad geographical region. See *Profile.*

**Residual Soil.*—Sedentary soils formed by the weathering of mineral material; by the disintegration and decomposition of rocks in place. See *Soil Genesis.*

**Reticulate.*—A natural arrangement of the soil mass in more or less regular-sized fragments separated by a network of narrow or hairline cracks. This arrangement of cracks may develop the coarse nut or the clod structure. See *Soil Structure.*

**Riverwash.*—Alluvial deposits in stream beds and flood channels, subject to erosion and deposition during recurring flood periods. Textures range from silts and sands to cobbles and bowlders. Usually free from vegetation other than occasional willows and some annual weeds.

**Rock Outcrop.*—Areas of outcropping bedrock of sufficient size to show on the maps. Smaller areas are usually included in the other rough-land classifications.

**Rough Broken Land.*—A condition of surface including badly eroded and dissected slopes, steep-sided V-shaped ravines, gullies, arroyos, and canyons, narrow inter-gorge ridges, and areas of bad-land that are of no agricultural value. It may include some very small areas of arable lands on small mesas or other remnants of original surfaces. Usually is bare of vegetation or has a cover of brush, weeds, or grasses.

**Rough Mountainous Land.*—This is an inclusive term used to cover a topography that is generally non-agricultural; mountain sides and slopes and the larger and steeper foothills and ridges. It includes bodies of arable soil, usually too small and irregular in outline to warrant separation and classification, but which may ultimately be cleared and put to agricultural production. The major portion of this classification is steep slopes, canyon walls, ridges, etc., of no agricultural value, but having sufficient soil to support a cover of trees, brush, or grasses. Where climatic conditions are favorable, it

is well suited to forestry, while in the more arid regions it may be utilized as range pasture.

**Rough Stony Land.*—A condition of surface so covered with rock fragments, stone, or bowlders as to be of no agricultural value. Includes rough, rugged, stony mountain slopes, steep, stony hill slopes, and stony and rocky areas of smoother topography. The presence of excessive amounts of surface stone and rock fragments is the determinant factor.

**Saline Soil.*—A soil containing excessive amounts of the neutral or non-alkaline salts, usually chlorides and sulfates. See *Alkali Soil; Alkaline Soil.*

Sand.—See *Soil Texture; Textural Grade; Texture.*

Sandy Loom.—See *Textural Grade; Texture.*

Saturated.—When the whole of the absorptive power of the soil is satisfied with metallic cations.

Saturation.—The filling to the utmost capacity for absorbing or retaining. The satisfying of the affinity of a material.

**Scabland.*—Mainly a non-agricultural condition, occupying areas of lava flows, where the surface consists of loose fragments of lava, outcroppings of the lava rock mass, with small pockets and patches of shallow accumulations of soil. These pockets support a growth of grass, brush, or small stunted trees. Occasionally a soil patch is cleared and cultivated, but the areas are usually too small and the soil too shallow to permit agricultural use. It usually includes small rocky hills, buttes, and ravine walls that are properly rough stony land, but the typical topography is broadly level or undulating with rough lava-stream surface.

**Secondary Soils.*—Soils developed through the accumulation and weathering of materials, originating from previously existing soils and from rock débris, that have been eroded from their former locations and re-deposited by the transporting agents. Transported soils. See *Soil Genesis.*

**Sedentary Soils.*—Soils formed in place without the addition of transported material. See *Soil Genesis.*

**Semi-Mature Soil.—(Solum Semimaturum.*—A soil having a profile with compact, semi-cemented horizons with high clay accumulations strongly weathered semi-mature soil. See *Soil Development.*

Separate.—See *Soil Separate.*

Series.—See *Soil Series.*

**Sharp.*—Containing angular particles in sufficient amount to dominate the "feel." Abrasive.

Silt.—See *Soil Texture.*

Silt Loam.—See *Textural Grade; Texture.*

**Single Grained.*—An incoherent condition of the soil mass with no arrangement of the individual particles into aggregates. Structureless. Usually found in soils of coarse texture. See *Soil Structure.*

Smooth.—Containing well-rounded coarser particles and a predominance of the finer separates. Not abrasive.

**Soft.*—A soil that yields readily to any force causing rupture or deformation. Aggregates readily crushed between fingers. See *Soil Consistence.*

**Soil.*—The soil is a natural body occupying the surface portion of the earth, composed of mineral and organic materials and having more or less definitely developed horizons of eluviation and illuviation. The term *soil,* as defined, includes both the solum and the upper portions of the underlying parent material; the A, B, and C horizons. It includes therefore the immature or relatively unweathered "soils" as well as those that have well-developed profile characteristics. Recent alluvial deposits of soil material, in which distinct A and B horizons may not be discernible, would be included in the "less definitely developed" soils. The definition is intended to cover all soil or "soil material" that may function as a soil.

Soil Age.—The terms indicating age are used to indicate a relative time in soil genesis or soil development. See *Soil Genesis; Soil Development; Time.*

**Soil Characteristics.*—Qualities, properties, or features that may serve to establish the character of a soil.

Soil Class.—See *Textural Grade.*

**Soil Consistence.*—Consistence is a term expressing the degree of cohesion of the soil and the resistance opposed to forces tending to deform or rupture the aggregates. Consistence and structure are closely related and frequently interdependent. The terms expressing consistence and structure are distinct, however, and need not be confused or used with double meaning. A study of published reports shows a general use of terms expressing both the consistence and the structure in nearly all soil descriptions. The following terms are used to express consistence—for definition, see *Brittle; Cemented; Cheesy; Compact; Firm; Friable; Hard; Impervious; Indurated; Loose; Mellow; Plastic; Soft; Sticky; Stiff; Tenacious; Tight; Tough.*

Soil Development.—See *Soil Age; Recent Soil; Young Soil; Immature Soil; Semi-mature Soil; Mature Soil; Aged Soil.*

**Soil Family.*—A group of soil series that are progressing toward a common or closely similar final mature profile condition. The "family" would include all soils, regardless of their stage of development, that were progressing toward the same mature profile characteristics, and would indicate an existence, for different periods of time, under uniform and similar conditions of climate, vegetative cover, and drainage. It might also indicate a common origin and mode of formation. See *Classification.*

**Soil Fertility.*—The capacity of a soil for production under the most favorable conditions. Soil fertility refers to the maximum productiveness under ideal conditions of climate and soil management, as in

a well-managed glass house where all environmental conditions could be controlled.

Soil Genesis.—The generation or origin of soils. See *Cumulose Soils; Mineral Soils; Organic Soils; Primary Soils; Residual Soil; Secondary Soils; Sedentary Soils; Transported Soils.*

Soil Porosity.—Porosity is a term indicating the mass effect of the pores or voids between the individual particles and aggregates that make up the soil. For descriptive terms, see *Cellular; Dense; Porous; Spongy; Tubular; Vesicular.*

**Soil Productiveness.*—The actual producing power of a soil under normally existing condition. Soil productiveness refers to the actual productiveness under the condition (of climate and other environmental features) generally encountered.

Soil Profile.—See *Profile.*

**Soil Province.*—A grouping of Soil Series and Families based on broad general resemblances in profile characteristics. The Province grouping now in use is based on similarities in *mode of formation*, as the Coastal Plains Province or the Glacial Province; to similar *origin*, as the Limestone Valley Province; or to certain similarities of *geologic* and *geographic* features, as the Piedmont Plateau Province, or the Appalachian Mountain and Plateau Province. See *Classification.*

**Soil Separate.*—One of the several grain-size groups into which the soil is separated by mechanical analysis.

**Soil Series.*—A group of soils having the same character of profile—(the same general range in color, structure, consistence, and sequence of horizons), the same general conditions of relief and drainage, and usually a common or similar origin and mode of formation. A group of soil types closely similar in all respects except the texture of the surface soils. While the soil type is the unit of soil mapping, the series is the most important in soil classification, as it expresses in full the profile differences. See *Classification.*

**Soil Structure.*—Structure is a term expressing the arrangement of the individual grains and aggregates that make up the soil mass. The structure may refer to the natural arrangement of the soil when in place and undisturbed or to the soil at any degree of disturbance. The terms used indicate the character of the arrangement, the general shape and the size of the aggregates and in some cases may indicate the consistence of those aggregates. For descriptive terms, see the following, to which the term structure is usually appended: *Adobe; Amorphous; Buckshot; Clod; Columnar; Crumb; Crust; Crust Mulch; Fluffy; Granular; Honeycomb; Lump; Laminated; Massive; Mealy; Mulch; Nut; Plate; Puddled, Pulverent; Reticulate; Single Grained; Structureless.* For a closely related term, see *Soil Consistence.*

**Soil Texture.*—Texture is a term indicating the coarseness or fineness of the soil; the amount or quantity of each of the grain-size group

of particles that constitute the soil. As the soil is usually made up of particles of widely varying size, the textural terms usually express the mass effect or the combined effect of all these grain sizes, but they may indicate the predominance (in quantity or in textural effect) of a certain group of grains. The textural composition is determined by mechanical analysis—a laboratory process of separating the soil into groups of grain sizes. The system of mechanical analysis used by the Bureau of Soils of the U. S. Department of Agriculture separates the soil into seven grain sizes or "separates" having the following size and name: (1) Fine gravel, 2 to 1 mm.; (2) Coarse sand, 1 to 0.5 mm.; (3) Sand, 0.5 to 0.25 mm.; (4) Fine sand, 0.25 to 0.10 mm.; (5) Very fine sand, 0.10 to 0.05 mm.; (6) Silt, 0.05 to .005 mm.; (7) Clay, 0.005 to indeterminate. See *Texture; Textural Grade.*

**Soil Tilth.*—Tilth is a term indicating the conditions of soil structure brought about by manipulation; an artificial structure produced by tillage or cultivation. Terms indicating the condition of tilth are the same as those indicating the soil structure under the broken or disturbed conditions, as mealy, pulverulent, granular, crumb, buckshot, mulch, nut structure, cloddy.

**Soil Type.*—A soil which throughout the full extent of its occurrence has relatively uniform texture of the surface soil and relatively uniform profile characteristics. The unit of soil mapping. The name of the soil type is a combination of series name and the textural grade designation, as, for example—Orangeburg sandy loam. See *Classification.*

**Solum.*—The weathered portion of the soil mass. The A and B horizons. See *Horizon A, Horizon B.*

**Spongy.*—A soil having a very large number of pore spaces of irregular shapes and sizes interconnected throughout the entire soil mass. See *Soil Porosity.*

**Sticky.*—A soil that shows a decided tendency when wet to adhere to other materials and objects. Adhesive rather than cohesive when wet, but usually very cohesive when dry. See *Soil Consistence.*

**Stiff.*—A soil that is resistant to deformation or rupture. A soil stratum or horizon that is firm and tenacious, and tending toward impervious. Usually applied to condition of the soil in *place* and when moderately wet. See *Soil Consistence.*

Stony.—See *Texture.*

**Stratum—Strata.*—A layer or layers of material whose character was established during the formation and is not due to subsequent alteration by weathering. In transported soils, there may be layers or strata of sand, silt, clay, or gravel, or of varying conditions with respect to structure and consistence, that may have an important bearing on the character of the soil, even influencing the effects of weathering agents. Hence in these definitions reference is made both to *horizons* and *strata.* See *Horizon.*

Structure.—See *Soil Structure*.

**Structureless*.—Without any discernible structure or arrangement of the soil particles into aggregates. This condition is better expressed by the terms—single-grained, massive, amorphous, etc. See *Soil Structure*.

**Subsoil*.—The horizons or layers of soil beneath the surface soils. The B horizons. When necessary, the subdivisional terms "upper subsoil," "lower subsoil," etc., are used. See *Stratum*.

**Substratum*.—The horizons or layers of material below the solum or true soil mass. The C horizons. In most cases the substratum is the deeper, unweathered parent material. In some soils, it may be materials quite distinct in character from that which weathered to form the overlying soil mass. In recent soils, where distinct A and B horizons may not exist, it usually is applied to strata distinctly different in color, texture, structure, or consistence from the upper or "soil" layers. See *Stratum*.

**Subsurface Soil*.—The horizon or layer of soil directly beneath the surface soil. The A horizons below Horizon A_1. In cases where the term "surface soil" is applied to the tilled portion of soils that are deep and uniform, it is used to include the portion of the uniform material below the tilled depth. See *Stratum*.

**Surface Soil*.—The upper horizon or surface layer of the soil mass. The horizons above Horizon A_2. In describing cultivated soils, it usually includes that portion that is modified by plowing and other tillage operations. In other cases, where the color of the upper portion of the soil mass is modified by accumulations of organic matter, it is applied to the full depth of that color horizon. See *Stratum*.

**Swamp*.—Flat, wet areas usually covered by standing water and supporting a growth of trees, shrubs, and grasses.

**Tailings and Culm Banks*.—Débris of dredger, placer, hydraulic mining, or stamp mills usually consisting of extensive areas of cobble and stone in piles or ridges, or of slopes or basins of slickens or other fine-textured wastes, and of the piles of waste at mine and tunnel mouths.

**Tenacious*.—A soil that shows a decided resistance to rupture. The soil mass coheres firmly. "Sticky" and "tenacious" are often used as synonyms, but in soil usage the former is taken to refer to adhesion, the latter to cohesion. Both may be present in a soil at the same time. See *Soil Consistence*.

Texture.—See *Soil Texture*. The A.S.S.A. committee on terminology offers the following: "In the field, texture is determined by the *feel* of the soil mass when rubbed between the fingers. The following statements give the obvious physical characteristics of the basic textural grades:

"*Sand*.—Sand is loose and single-grained. The individual grains can readily be seen or felt. Squeezed in the hand when dry, it will

fall apart when the pressure is released. Squeezed when moist, it will form a cast, but will crumble when touched.

"*Sandy Loam.*—A sandy loam is a soil containing much sand but which has enough silt and clay to make it somewhat coherent. The individual sand grains can readily be seen and felt. Squeezed when dry, it will form a cast which will readily fall apart; but if squeezed when moist, a cast can be formed that will bear careful handling without breaking.

"*Loam.*—A loam is a soil having a relatively even mixture of the different grades of sand and of silt and clay. It is mellow with a somewhat gritty feel, yet fairly smooth and slightly plastic. Squeezed when dry, it will form a cast that will bear careful handling, while the cast formed by squeezing the moist soil can be handled quite freely without breaking.

"*Silt Loam.*—A silt loam is a soil having a moderate amount of the fine grades of sand and only a small amount of clay, over half of the particles being of the size called 'silt.' When dry it may appear quite cloddy but the lumps can be readily broken, and when pulverized it feels soft and floury. When wet, the soil readily runs together. Either dry or moist, it will form casts that can be freely handled without breaking, but when moistened and squeezed between thumb and finger, it will not 'ribbon' but will give a broken appearance."

"*Clay Loam.*—A clay loam is a fine-textured soil which usually breaks into clods or lumps that are hard when dry. When the moist soil is pinched between the thumb and finger, it will form a thin 'ribbon' which will break readily, barely sustaining its own weight. The moist soil is plastic and will form a cast that will bear much handling. When kneaded in the hand, it does not crumble readily, but tends to work into a heavy compact mass.

"*Clay.*—A clay is a fine-textured soil that usually forms very hard lumps or clods when dry and is quite plastic and usually sticky when wet. When the moist soil is pinched out between the thumb and fingers it will form a long, flexible 'ribbon.' Some fine clays very high in colloids are friable and lack plasticity in all conditions of moisture.

"*Gravelly or Stony Soils.*—All of the above grades of soil, if mixed with a considerable amount of sand, gravel or stone, are designated as sandy clay loams, sandy clays, etc., as gravelly sandy loams, gravelly clays, etc., or as stony sandy loams, stony loams, etc."

For soils having texture different from the above, see *Muck; Peat.*

**Textural Grade (Soil Class).*—A classification of soils based on texture alone. This is the "soil class" in general American usage, but as the term "class" is generally used for a more inclusive grouping, a

designation of higher order, in nearly all schemes of classification, "textural grade" or "grade" is recommended as a better term for this use. The following table shows the proportions of the grain sizes found in the major textural grades (from U.S.D.A. Circular 419):

1. Soils containing less than 20 per cent clay:
   Soils containing less than 15 per cent silt and clay:
   Sand:
   Coarse sand (35 per cent or more fine gravel and coarse sand, and less than 50 per cent fine or very fine sand).
   Sand (35 per cent or more fine gravel, coarse and medium sands, and less than 50 per cent fine or very fine sand).
   Fine sand (50 per cent or more fine and very fine sands).
   Very fine sand (50 per cent or more very fine sand).
   Soils containing from 15 to 20 per cent silt and clay:
   Loamy sand:
   Loamy coarse sand (35 per cent or more fine gravel and coarse sand, and less than 35 per cent fine and very fine sand).
   Loamy sand (35 per cent or more fine gravel, coarse, and medium sands, and less than 35 per cent fine and very fine sand).
   Loamy fine sand (35 per cent or more fine and very fine sand).
   Loamy very fine sand (35 per cent or more very fine sand).
   Soils containing from 20 to 50 per cent silt and clay:
   Sandy loam:
   Coarse sandy loam (45 per cent or more fine gravel and coarse sand).
   Sandy loam (25 per cent or more fine gravel, coarse and medium sands, and less than 35 per cent very fine sand).
   Fine sandy loam (50 per cent or more fine sand, or less than 25 per cent fine gravel, coarse and medium sand).
   Very fine sandy loam (35 per cent or more very fine sand).
   Soils containing 50 per cent or more silt and clay:
   Loam and silt loam:
   Loam (less than 20 per cent clay, from 30 to 50 per cent silt, and from 30 to 50 per cent sand).
   Silt loam (less than 20 per cent clay, 50 per cent or more silt, and less than 50 per cent sand).
2. Soils containing from 20 to 30 per cent clay:
   Clay loam:
   Sandy clay loam (less than 30 per cent silt, and from 50 to 80 per cent sand).
   Clay loam (from 20 to 50 per cent silt, and from 20 to 50 per cent sand).
   Silty clay loam (from 50 to 80 per cent silt, and less than 30 per cent sand).
3. Soils containing 30 per cent or more clay:

Clay:
Sandy clay (from 30 to 50 per cent clay, less than 20 per cent silt, and from 50 to 70 per cent sand).
Clay (30 per cent or more clay, less than 50 per cent silt, and less than 50 per cent sand).
Silty clay (from 30 to 50 per cent clay, from 50 to 70 per cent silt, and less than 20 per cent sand).

**Tidal Marsh.*—Low, flat marsh lands traversed by interlacing channels and tidal sloughs and usually inundated by high tides. Supports a cover of salt-marsh vegetation, usually low growing plants, with areas of rushes and reeds.

**Tight.*—A term applied to strata or horizons of the soil that are compact, impervious, and tenacious, and usually plastic. See *Soil Consistence.*

Time.—In regard to soil culture, etc., may be specifically designated. In regard to soil genesis, is relative, *i.e.* relative from the standpoint of time as used geologically. See *Soil Age.*

**Tough.*—A soil that is resistant to rupture. Tenacious. A term applied to strata or horizons of the soil that can be readily bored into with the auger but which requires much force in breaking loose and pulling out the core of the soil. See *Soil Consistence.*

**Transported Soils.*—Soils formed by the consequent or subsequent weathering of materials transported and deposited by some agency such as water, air, or ice. Secondary Soils. See *Soil Genesis.* The following subdivisions of secondary and transported soils refer primarily to the agencies which transported and deposited the soil material from which the soil is developed by weathering. They do not necessarily enter into any scheme of soil classification but may in some instances be very useful in indicating the cause of variations in the weathered soils as well as in the parent material. See *Æolin Soil; Alluvial Soil; Glacial Soil; Lacustrine Soil; Loessal Soil; Marine Soil; Old Valley-Filling Soil; Recent Valley-Filling Soil.*

**Tubular.*—A soil in which the pore spaces are more or less regular in size and are connected to form tube-like voids. See *Soil Porosity.*

Type.—See *Soil Type.*

**Typical Profile.*—A profile definitely representative of a soil type or a soil series. The standard of the type or series. In practice the typical profile of a new type or series is determined as soil study proceeds and repeated borings and examinations develop the prevailing characteristics of the particular type or series. Established series have their typical profile characteristics recorded, and in mapping these characteristics must be kept in mind, together with the degree of deviation permissible. See *Profile.*

Unavailable.—A condition of the soil constituents in relation to plants, compounds, or elements in such form of combination or under such

soil conditions as to become available so slowly that plants cannot secure sufficient nutrients for growth. See *Plant Food Element*.

Unsaturated.—When hydrogen ions are among the ionizable cations in the soil mass.

**Velvety*.—Very smooth-textured, free from any coarse particles, usually free from any except the smallest aggregates.

**Vesicular*.—A soil containing many small rounded cavities or pores, smooth on the inside as though formed by gas bubbles. See *Soil Porosity*.

**Young Soil* (*Solum Semicrudum*).—A soil having a profile with slightly compact subsoil horizons, but without distinct clay accumulations; slightly weathered immature soil. See *Soil Development*.

AUTHORS' INDEX

GENERAL INDEX